THE CLIMATIC, BIOLOGICAL, AND STRATEGIC EFFECTS OF NUCLEAR WAR

HEARING

BEFORE THE

SUBCOMMITTEE ON NATURAL RESOURCES,
AGRICULTURE RESEARCH AND ENVIRONMENT

OF THE

COMMITTEE ON
SCIENCE AND TECHNOLOGY
HOUSE OF REPRESENTATIVES

NINETY-EIGHTH CONGRESS

SECOND SESSION

SEPTEMBER 12, 1984

[No. 126]

Printed for the use of the
Committee on Science and Technology

U.S. GOVERNMENT PRINTING OFFICE
39-934 O WASHINGTON : 1985

H701-41

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THE CLIMATIC, BIOLOGICAL AND STRATEGIC EFFECTS OF NUCLEAR WAR

WEDNESDAY, SEPTEMBER 12, 1984

HOUSE OF REPRESENTATIVES, COMMITTEE ON SCIENCE AND
TECHNOLOGY, SUBCOMMITTEE ON NATURAL RESOURCES,
AGRICULTURE RESEARCH AND ENVIRONMENT,
Washington, DC.

The subcommittee met, pursuant to call, at 9:45 a.m., in room 2318, Rayburn House Office Building, Hon. James H. Scheuer (chairman of the subcommittee) presiding.

Mr. SCHEUER. All right, the meeting of the Subcommittee on Natural Resources, Agriculture Research and Environment will come to order.

As all of you know, we're racing the clock to adjourn in the first week of October and these are very, very hectic days and weeks for all of us, and we're all overburdened and overscheduled and stretched to the breaking point. I say this by way of explanation for the fact that my colleagues haven't arrived yet. They're expected and I hope they'll be here soon, but in deference to all of your time, and in deference to the courtesy of the witnesses in coming here, I don't suppose we ought to wait any longer, so we will proceed.

Scientists, like the ones we will be hearing today, believe that 65 million or so years ago, much of life on Earth was extinguished by a sudden catastrophic impact between our planet and an asteroid. That was the end of dinosaur life on Earth.

In the past year, a number of scientists have begun to warn us that mankind now has the power to affect long-term biological and climatic changes unrivaled since that primordial collision 65 million years ago. They hypothesized that quite apart from short-term effects due to explosions, heat, and radiation and the problems of dust, soot, smoke, and ash, which are generated thereby, that a nuclear exchange involving today's enormous nuclear arsenals, even as little as 1 to 10 percent of the current nuclear arsenal, could lead to a chilling darkness that could last months or even years, threatening the very ability of Earth to sustain life.

It would, in truth, be a nuclear winter. Now, if this hypothesis is correct even on a worst-case theory, then the implications of this hypothesis impose new realities on our thinking about nuclear deterrence. The first logical outgrowth of that theory is that no one, not even an aggressor nation which totally and preemptively, perhaps, destroyed its opponent's arsenals could win a nuclear confrontation or even survive because detonating a sufficient number of weapons in itself would be the equivalent of global suicide.

A corollary to all of that is that nations and peoples—North, South, East, and West—would become together inextricably involved in the long-term consequences of any nuclear exchange. And perhaps even more important, if the theory is correct, that we would achieve this nuclear winter, as I said a moment ago, even with a very small percentage of the world's nuclear arsenals involved, anywhere from 1 to 10 percent.

Now, we have convened these hearings today, not to espouse a particular point of view or to take a partisan stance on these issues, but to illuminate for the public and for ourselves in Congress what is clearly a set of the day's most transcendentally important issues.

We are very fortunate to have several panels before us today, including some of this country's most eminent scientists and from them, we will hear views on how solid this nuclear winter theory really is, what the level of uncertainty, what the problematical characteristics of this theory are which underlie its assumptions and its consequences. That will be the mission of this first panel.

Then we will discuss research efforts, both in this country and abroad, which are directed at reducing these uncertainties, and this discussion will be particularly helpful to members here today since I believe that soon, and perhaps even before this Congress terminates on or about the 5th of October, the House may well be considering structuring and funding the Federal research program.

And from our final panel, we will hear a range of views on the importance that the nuclear winter hypothesis may hold for our nuclear strategic planning.

[The opening statement of Mr. Scheuer follows:]

OPENING STATEMENT BY HON. JAMES H. SCHEUER ON NUCLEAR WINTER
SEPTEMBER 12, 1984

Scientists believe that 65 million years ago, much of life on earth was extinguished by the sudden, catastrophic impact between our planet and an asteroid. This collision spawned enormous dust clouds, which obliterated the sun and led to a dark and uncompromising global winter. The largest and most powerful creatures on Earth -- the dinosaurs -- apparently perished from the aftereffects of the collision.

In the past year, a number of prominent scientists have begun to warn us that mankind now has the power to effect long-term biological and climatic changes unrivalled since that primordial collision. They hypothesize that, quite apart from short-term effects due to explosions, heat, and radiation, an exchange involving today's enormous nuclear arsenals could lead to chilling darkness, lasting months or even years, which would threaten the very ability of the Earth to sustain itself. It would be a "nuclear winter."

If the nuclear winter hypothesis is correct, the implications impose new realities on our thinking about nuclear deterrence. The first logical outgrowth of the theory is that no one -- even an aggressor nation which totally and preemptively destroyed its opponent's arsenals, could win a nuclear confrontation. Detonating a sufficient number of weapons would, in itself, be suicidal. A corollary is that all nations and all peoples -- East and West, North and South, involved and neutral -- would become inextricably involved in the long-term consequences of the exchange. And perhaps most importantly, if the theory is correct, these consequences would flow from an exchange involving only a small fraction -- perhaps 1 to 10 percent -- of the world's nuclear stockpiles.

We have convened today's hearings, not to take a particular point-of-view or partisan stance on these issues, but to illuminate for the public and for the Congress what is clearly a set of important issues. From a panel including some of this country's most eminent scientists, we will hear views on how solid the nuclear winter theory really is -- that is, we will consider the level of uncertainty underlying both its assumptions and its consequences. Next we will discuss the research efforts, both in this country and internationally, which are directed at reducing these uncertainties. This discussion will be particularly helpful to Members here today, since I believe that soon -- perhaps even later this month -- the House will consider the structure and funding of the Federal research program. And from our final panel today, we will hear a range of views on the importance that the nuclear winter hypothesis holds for our nuclear strategic planning.

Let me say a final word about our purpose today of helping to bring the issue of nuclear winter into the public's consciousness. In recent years, public debate on issues concerning nuclear deterrence and security has sharply increased. This is a healthy phenomenon, since all policy -- Democratic or Republican, East or West -- should consider public views. At the same time, these public views, even on a subject as inherently depressing as the one which confronts us today, should not arise from ignorance and fear. As much as is possible, the public debate must proceed from a careful scientific basis and be guided by the best evidence available. Our intent today will be to air this evidence as openly as we can.

Mr. **Scheuer**. So at the present time, we will get on with our first panel. They will speak to you in order. First, Carl Sagan, Stephen Jay Gould, and Edward Teller.

Carl Sagan is the David Duncan professor of astronomy and director of the Laboratory for Planetary Studies at Cornell University. He is probably best known as the host for the popular television show, "Cosmos," which we've all seen and enjoyed and benefited from. He's a Pulitzer Prize winner, has authored 11 books and edited 9 scientific journals, including "Origin of Life," "Climatic Change," and "Science 1980."

In 1983, Dr. Sagan and four other scientists coauthored a study which was published in Science Magazine, which stimulated much of the current interest in nuclear winter.

Dr. Sagan, why don't you take approximately 8 or 10 minutes, and then we'll go on with the other two witnesses and then we'll have some discussion.

We're delighted to have you here today.

STATEMENTS OF DR. CARL SAGAN, DIRECTOR, LABORATORY FOR PLANETARY STUDIES, CORNELL UNIVERSITY; DR. STEPHEN JAY GOULD, PROFESSOR OF GEOLOGY, HARVARD UNIVERSITY; AND DR. EDWARD TELLER, LAWRENCE LIVERMORE NATIONAL LABORATORY

Dr. **Sagan**. Thank you, Representative Scheuer, I'm very pleased to be here as well.

I'll try to be very brief because at least on the issue of whether the subject of nuclear winter should be funded to reduce any existing uncertainties, I think everyone—at least on this panel—is agreed that it should be.

Mr. **Scheuer**. Dr. Sagan, before you get into your testimony, let me welcome our colleague, Congressman Ray McGrath, of Long Island. He and I are comembers of the Long Island delegation. He's a distinguished member of the New York delegation. We're delighted to have him with us.

Excuse me, go ahead. Proceed, Dr. Sagan.

Dr. **Sagan**. Thank you.

Briefly, the—the first step on the road to uncovering nuclear winter came in 1971 when the Mariner 9 spacecraft was in orbit around Mars, and examined for many months a global dust storm which had the interesting property of warming the upper atmosphere considerably and cooling the surface of Mars considerably. That was a suggestion that fine particles in a planetary atmosphere can heat the atmosphere, cool the surface and drive from the heating of the atmosphere the fine particles over the Equator into the opposite hemisphere.

We were able to calculate what the effects would be; found that they were comparable to what was observed, and later used that computational armamentarium to calculate what the consequences for the Earth's climate would be of large volcanic explosions which characteristically cool the Earth by fraction of a degree—not from dust, but mainly liquid sulfuric acid droplets punched into the stratosphere.

Then my colleagues, but not myself, addressed the issue that you, Representative Scheuer, began your remarks with, the question of the massive floral and faunal extinction 65 million years ago, which led to the extinction of the dinosaurs and many other species, and which is now widely but not universally thought to be due to the impact on the Earth of an asteroid or cometary nucleus, the projection of a large cloud of fine silicate particles cooling and darkening the Earth and that is generally thought to have been the event that led to a lot of grief for a lot of inhabitants of the Earth at the cretaceous/tertiary transition 65 million years ago.

Only then did we—we—the names of the authors are Turco, Toon, Ackerman, Pollack and myself—briefly called the TTAPS group, a not inappropriate acronym considering the nature of the results—only then did—did we think of seriously working on the nuclear war issue. We were thinking at first only of dust. There was then an important paper by Crutzen and Birks which talked about soot. They talked mainly about soot from the burning of forests in a nuclear war. They talked about substantial darkening of the Northern Hemisphere, but did not talk about cooling.

We then calculated for a wide range of cases, some 50 different scenarios and variations of uncertain parameters over their plausible range, what the consequences of various nuclear wars might be, and found, to our great surprise, because this was—or at least should have been a well-studied area—that a large number of scenarios yielded absolutely catastrophic results, locally, hemisphere-wide and probably globally.

The—the work was presented at a number of forums, reviewed by a very large number of scientists, published in the refereed journal, Science. There have been a number of confirmatory calculations subsequently. Vladimir Aleksandrov of the Computing Centre of the Soviet Academy of Sciences, who is here, did the first global circulation model on nuclear winter. Alan Robock of the University of Maryland, who is here, has done an important recent study suggesting that the effects would persist considerably longer than we calculated in the TTAPS paper.

Let me stress that there necessarily are uncertainties in any calculation of this sort. Nuclear war is not a problem that is amenable to experimental verification, or at least not more than once, and we do not wish to perform the experiment. The results, therefore, have to depend upon laboratory and field measurements, of single nuclear weapons explosions and fires set intentionally and unintentionally, laboratory results and theoretical calculations involving some of the most difficult aspects of classical physics, hydrodynamics of a complex weather system.

There are differences of opinion, although I must say that the great bulk of the published work suggests that the original TTAPS results are somewhere in the neighborhood of what might happen, and curiously enough, this also seems to be the opinion of the Department of Defense in a—in testimony before the Joint Economic Committee last July 12, Mr. Richard Wagner, Assistant to Defense Secretary Weinberger, said: "There would be a nuclear winter," even if there was an exchange at comparatively low yields.

The fact that the Department of Defense takes this seriously is—is welcome news. It doesn't mean that they're right; the Department of Defense has been mistaken in the past and doubtless will be mistaken in the future, but I stress this convergence of opinion to indicate that a wide variety of different points of view seem to agree that this is something very serious.

There are a number of effects that have been identified which tend to ameliorate the consequences as discussed in the TTAPS results and a number of effects which have been identified which tend to make them worse. It is my opinion, the opinion of my colleagues, that in balance, the TTAPS results are, in fact, conservative, and that—especially on the duration of nuclear war—of nuclear winter—would probably be considerably longer than the few months that we calculated in our paper, and I can, in the question period, explain why if anyone is interested.

There are issues of how much smoke is produced in the burning of a city or a forest; how big the particles are; how much the particles absorb; how high the plume of smoke rises; how fast the particles coagulate; how readily the particles are carried out by rainfall; the circulation of the resulting dust and soot—the possibility of intermittent early patchiness in the distribution of clouds, all of which deserve serious consideration. Some of those, as I said, might make things better; some might make things worse.

There was a—there was and is at this moment a—conference at the National Bureau of Standards sponsored by the Defense Nuclear Agency on fire phenomenology. Dr. Teller talked there Monday; I talked there yesterday, and it is an indication of a great deal of serious work that—that is beginning to occur.

There are a range of aspects of the problem that have not been examined and which tend to make things worse. Multiburst phenomena, for example: one nuclear explosion propelling the debris from the previous nuclear explosion well up into the stratosphere; tactical nuclear weapons, of which there are only 35,000 in the world, none of which have been involved in the previous scenarios; the kind of feedbacks involving sea ice and increased snow that Allan Robock has identified, which tend to make the effects longer; the production of toxic gases from the burning of synthetics in modern cities; and even more dire possibilities.

Clearly, it's important to narrow the range of uncertainty, especially because there are, as Representative Scheuer said in his opening remarks, a set of very serious possible implications for policy and strategy and doctrine if nuclear winter turns out to have even a small chance of being as severe as we say it is. And this includes the very interesting idea that first strikes are self-deterring because the attacked nation need not lift a finger to protect itself or defend itself and the aggressor nation will be destroyed by the cloud of soot and smoke that circulates back to the aggressor nation. It implies that crisis relocation and civilian shelters are even more bankrupt ideas than before nuclear winter. It suggests that nations in parts of the world far distant from the conflict, with no particular role in the quarrel between the antagonists might be utterly destroyed without a single nuclear weapon falling on their territories, and therefore, the stake of other nations in what the United States and the Soviet Union choose to do with the world would have risen significantly.

There are other implications involving possible restructuring of arsenals which I disagree with and on massive reductions in the strategic arsenals of the United States and the Soviet Union, which I think is implied by these results. There are implications for war-fighting plans in Europe because even a tactical nuclear war, it now looks, might be able to trigger nuclear winter, but I mention these not because I think that that is the issue before us, but merely to indicate how high the stakes are.

Now, to take something seriously doesn't mean that you have to believe that the probability is extremely high. As I said before, I think the likelihood of a nuclear winter is high. I think we have on balance been conservative, but that need not be the case and still you would want to take nuclear winter very seriously.

I remind you that if there is a chance of some unlikely but unpleasant event—your house being washed away by a flood, say—customarily you don't say, "Well, the chance is small, so I won't worry about it." You take out insurance so that if the unlikely but unpleasant event occurs, you, in some way, are prepared. You also do research to know what the likelihood is and you try to build your house in some place which is less likely to be washed away by floods.

In actuarial statistics, the insurance companies determine what your premium should be by multiplying the probability of the event, known poorly, and how much you're going to lose if the event occurs, known better. It's that product, that multiplication, which determines how much insurance premium you pay.

The consequences of nuclear winter are so severe—Dr. Gould will describe the biological effects in a moment—that even if there were a tiny chance that this was right, you would want to be sure you had done the very best job you could. I believe that no matter what is done, there will be lingering uncertainties and we will have to—as often is the case in policy matters—deal with a circumstance where we do not understand everything.

There is a national plan for dealing with nuclear winter, which is being organized by Dr. Hecht, of the National Climate Program Office, from whom you will hear later this morning. I have had the opportunity to review the latest version of this plan. It is still undergoing modification, but I believe it is sound, sensible, broadly based, does not—it is not based on any bias about high probability or high improbability of nuclear winter. It is a sober approach to a very important question and I believe deserves the support of the authorization and funding committees of both Houses of Congress.

The—the study also has importance for fundamental atmospheric science, quite apart from the nuclear winter, and is a—an important way—it's not the only or the best way, but it is an important way to increase the level of maturity and sophistication of atmospheric sciences.

So, Mr. Chairman, I think I will stop here and I'm happy to respond to any questions and I also have some visuals if questions that are relevant to those visuals come up.

Mr. SCHEUER. Thank you very much, Dr. Sagan.

Let me say that after the three witnesses have testified, that we'll ask them some questions and then we would like to ask the—we would like to ask the panel to address any questions they may have in mind to each other. This is not unprecedented; it has happened from time to time, and with a small and very knowledgeable panel, you can sometimes get some extremely interesting colloquy. So as each of you testify, it may stimulate some questions in your two colleagues.

All right—and that will come immediately after a few—some brief questioning up here.

Stephen Jay Gould is MacArthur Foundation—is a MacArthur Foundation prize fellow and a professor of geology at Harvard University. He is author of the monthly column, "This View of Life," in Natural History magazine and has authored five books. He is widely recognized as one of the most seminal evolutionary biologists and as one of the best scientific communicators of our time.

I am reliably informed that his courses at Harvard University are systematically oversubscribed.

We are very happy to have you here, Dr. Gould, please proceed as you wish for approximately 10 minutes.

Dr. Gould. Moses terrified Pharaoh with a pall over Egypt, you'll remember. "He sent a thick darkness over all the land, even darkness which might be felt." But Moses' plague lasted only 3 days. The much longer darkness of nuclear winter, with its associated set of consequences, including plummeting temperatures, increased radiation, fires, enhanced chemical pollution of atmosphere and surface waters, has made the prospect of nuclear war even more terrifying than terrified humanity had previously imagined.

Some critics have charged that nuclear winter is too uncertain a phenomenon to merit much serious study. After all, the experiment has not, thank goodness, been tried, and science relies on repeatable tests. I would make two responses, both leading to the conclusion that more attention and effort must be devoted to this new and realistic threat. First, styles of legitimate scientific inquiry are far richer and more varied than the stereotype of the simple controlled experiment would indicate.

The science of complex historical events, including, for example, most of geology, much of astronomy, and all of my own field of paleontology, cannot work by traditional experiment because its events are too multifaceted and broad in scope. These sciences, equal in extent, importance, and testability with disciplines based on conventional experiment, use other methods to assess their theories and conclusions: For example, modeling complex events by measuring the effects of individual components and studying their modes of interaction and comparison with analogous historical events based on similar inputs.

The argument for nuclear winter is based on both these strategies. It emerges as a predictable consequence of our best atmospheric and meteorological models and it occupies a proper place in the continuum of actual events based on the same scenario, from smaller effects in historical volcanic eruptions to the much larger results of mass extinction in the geological record.

Indeed, the experiment of nuclear winter has probably been made upon our Earth, perhaps often. The geological record is punctuated by events of mass extinction, perhaps occuring at regular intervals of 26 million years and wiping out, in the worst case—and this is not a conjecture; this is a measurement—as many as 95 percent of marine invertebrate species. The causes of mass extinction have until recently been the greatest unsolved problem in paleontology, but since 1980, we've developed evidence, in the form of chemical signatures incorporated in the sediments at extinction boundaries, that at least the most famous of all such events, the Cretaceous dying that wiped out dinosaurs, along with some 50 percent of all recorded species, was a complex result of impact by comet or asteroid. The killing scenario for such an extinction developed by Luis Alvarez and his coworkers, invokes a cloud of dust lofted by the impact that made the Earth so cold and dark that most life perished—in other words, the same phenomenon as nuclear winter.

Now, one may take the very long view and point out that such extinctions are nature's plow, clearing away incumbents and making room for the evolution of new creatures——

Mr. SCHEUER. Excuse me, Dr. Gould. Your choice of language—the use of that phrase, "incumbents," has caused a certain amount of disquietude here. [Laughter.]

Dr. GOULD. Just to folks who are around at the moment. Good old vernacular——

Mr. SCHEUER. You've——

Dr. GOULD [continuing]. And I realize it has another meaning.

Mr. SCHEUER. You're concentrating our minds. [Laughter.]

Please proceed.

Dr. GOULD. Good old Webster definition, part of current context.

Indeed, had dinosaurs not been exterminated, the ecological space for large mammals would not have opened and we would probably not be in our current predicament, or here at all for that matter. But whatever the effect upon potential innovations, mass extinction can only be designated a disaster for incumbents; that is, all of us, and we are incumbents, all of us, upon our current Earth.

I shall not comment upon the physical models for nuclear winter developed by my colleagues, except to say that I am impresed both with the convergence of basic results reached by several independent simulations, performed both in America and in the Soviet Union, and by the substantial agreement about their plausibility and importance reached by so many distinguished scientists representing a complete spectrum of political attitudes—by the way—at meetings arranged to study the results prior to their publication in Science Magazine on December 23, 1983. Nuclear winter is not the fanciful conjecture of a few, but the result of a remarkable convergence among scientists throughout the world and representing such varied concerns as mass extinction in paleontology, the study of planetary atmospheres, the geology of impacts, atmospheric physics, and global climatic modeling. Rarely has any scientific study been subjected to such widespread scrutiny before publication.

Biological results—my subject today—are vastly more complicated and subject to uncertainty than the physical effects that yielded the basic model of nuclear winter. I will not, therefore, enumerate specific predictions.

What we can say virtually for certain is that the biological impact will be severe, perhaps irreversibly disastrous, as in the mass extinctions of our geological record. Since plausible models of nuclear winter reduce light to 1 percent of current ambient levels and depress summer temperatures to minus 40 degrees Centigrade in continental interiors of midlatitudes, the biological effect can scarcely be mild.

Admittedly, effects of this magnitude accompany one of the more severe versions of nuclear winter, but by no means the worst among plausible scenarios. Yet, acceptable and traditional planning for disaster, as both Representative Scheuer and Dr. Sagan just emphasized, must base its preparations on scenarios at the severe end of reasonable prediction. Remember the Titanic when you don't do it that way.

Three general principles of biological systems engender the uncertainty of specific predictions, but also lead to the general conviction that biological effects of nuclear winter might be both immediate and severe. First, the complexity of interactions. Biological systems contain more complex and interacting components than any other piece of nature. Impacts upon one species or local population may propagate up and down food chains and through ecosystems in waves of increasing severity.

If we lose much oceanic phytoplankton through suppression of photosynthesis by low light levels of nuclear winter, for example, we may impact the entire ecosystem of the sea, since the microscopic plankton lie at the base of marine food chains, with disastrous effects upon human fisheries.

Second, the small tolerance of certain biological systems, particularly those artificially maintained by human intervention—and by that, I mean primarily agriculture. Some, though not all, biological systems are well buffered by evolutionary history against environmental fluctuations, though not necessarily to the unexperienced effects of nuclear winter, but many biological systems most crucial to human life—the agriculture of major cereal grains, in particular—are artificially maintained by necessary massive continuous human input.

These might collapse completely on the assault of nuclear winter. Most cereal fields are unstable monocultures—often grown at the edges of ecological possibility—made of genetically uniform stocks; therefore, unusually susceptible to disease and dependent upon inputs of fertilization and irrigation that would almost surely be cut off after nuclear exchange.

Third, synergisms, or in technical parlance, nonadditive interactions. We cannot, in assessing the impact of disaster upon natural systems, simply add up the predictable effect upon each component separately in order to measure the response of the whole. Bad plus bad need not yield twice as bad, but often many times worse. For example, the intense radiation of a nuclear war might produce, by mutation, a new and potent agent of microbial disease. The effect of such a vector might then be heightened by several other impacts of radiation: General weakness of organisms by radiation sickness and particular suppression of immune systems that might otherwise fight disease.

Now, we must distinguish between two types of scales of biological effects for nuclear winter: First, the immediate increment of human suffering; and second, the long-term impacts upon ecosystems, including extinctions. Most uncertainties involve the second category of long-term effects, and these potential results are admittedly more spectacular. But effects of the first category—the immediate increment of human suffering—are much clearer and more than enough in themselves to justify our deep concern.

Although long-term effects are hard to predict, I might simply cite the last section, labeled "Conclusions," from the original paper written by 20 biologists and published as a companion piece to the original TTAPS report on nuclear winter. This is a long quote and I'm running overtime, so I'll quote just the last paragraph, but the entire quote is in my statement.

> Whether any people would be able to persist for long in the face of highly modified biological communities, novel climates, high levels of radiation; shattered agricultural, social and economic systems, extraordinary psychological stresses, and a host of other difficulties is open to question. It's clear that the ecosystem effects alone resulting from a large-scale thermonuclear war could be enough to destroy the current civilization, at least in the Northern Hemisphere. Coupled with the direct casualties of over a billion people, the combined intermediate and long-term effects of nuclear war suggest that eventually there might be no human survivors in the Northern Hemisphere.
>
> Furthermore, the scenario described is by no means the most severe that could be imagined with present world nuclear arsenals and those contemplated for the near future. In any large-scale nuclear exchange between the Superpowers, global environmental changes sufficient to cause the extinction of a major fraction of the plant and animal species on the Earth are likely. In that event, the possibility of the extinction of *Homo sapiens* cannot be excluded.

Sobering as these long-term possibilities may be, we need not venture beyond the immediate and much more clearly predictable increment in human suffering to seal our conviction that nuclear winter represents a great danger heretofore unrecognized. The probable collapse of Northern Hemisphere agriculture in a crowded and hungry world is potential disaster enough.

The prospect of nuclear winter, however frightening, may at least—and at last—teach us that we are truly one world and that the result of nuclear war for any one nation could only be the most ultimately pyrrhic of all possible victories.

Thank you.

[The prepared statement of Dr. Gould follows:]

A Personal Statement on the Biology of Nuclear Winter

Stephen Jay Gould

Museum of Comparative Zoology
Harvard University
Cambridge, Mass. 02138

Moses terrified Pharaoh with a pall over Egypt: "He sent a thick darkness over all the land, even darkness which might be felt." But Moses' plague lasted only three days. The much longer darkness of nuclear winter, with its associated set of consequences, including plummeting temperatures, increased radiation, fires, and enhanced chemical pollution of atmosphere and surface waters, has made the prospect of nuclear war even more frightening than terrified humanity had previously imagined.

Some critics have charged that nuclear winter is too uncertain a phenomenon to merit much serious study: after all, the experiment has not (thank goodness) been tried, and science relies on repeatable test. I would make two responses, both leading to the conclusion that more attention and effort must be devoted to this new and realistic threat. First, styles of legitimate scientific inquiry are far richer and more varied than the stereotype of the simple controlled experiment would indicate. The science of complex historical events, including, for example, most of geology, much of astronomy and all of my own field of paleontology, cannot work by traditional experiment because its events are too multifaceted and broad in scope. These sciences, equal in extent, importance and testability with disciplines based upon conventional experiment, use other methods to assess their theories and conclusions: for example, modelling complex events by measuring the effects of individual components and studying their modes of interaction, and comparison with analogous historical events based on similar inputs. The argument for nuclear winter is based upon both these strategies: it emerges as a predictable consequence of our best atmospheric and meterorological models, and it occupies its proper place in a continuum of actual events based on the same scenario -- from smaller effects in historical volcanic eruptions to the much larger results of mass extinction in the geological record.

Indeed, the experiment of nuclear winter has probably been made upon our earth, perhaps often. The geological record is punctuated by events of mass extinction, perhaps occurring at regular intervals of 26 million years, and wiping out, in the worst case, as many as 95 percent of marine invertebrate species. The causes of mass extinction have, until recently, been the greatest unsolved problem in paleontology. But, since 1980, we have developed evidence, in the form of chemical signatures incorporated in the sediments at extinction boundaries, that at least the most famous of all such events -- the Cretaceous dying that wiped out dinosaurs along with some 50 percent of all recorded species -- was a complex result of impact by comet or asteroid. The "killing scenario" for such an extinction, developed by Luis Alvarez and his coworkers, invokes a cloud of dust, lofted by the impact, that made the earth so cold and dark that most life perished -- in other words, the same phenomenon as nuclear winter.

One may take the very long view and point out that such extinctions are nature's plow -- clearing away incumbents and making room for the evolution of new creatures. Indeed, had dinosaurs not been exterminated, the ecological space for large mammals would not have opened, and we would probably not be in our current predicament.(or here at all for that matter). But, whatever the effect upon potential innovations, mass extinction can only be designated a disaster for incumbents -- and we are incumbents upon our current earth.

I shall not comment upon the physical models for nuclear winter developed by my colleagues -- except to say that I am impressed both with the convergence of basic results reached by several independent simulations performed both in America and in the Soviet Union, and by the substantial agreement about their plausibility and importance reached by so many distinguished scientists, representing a complete spectrum of political attitudes by the way, at meetings arranged to study the results prior to their publication in Science magazine on December 23, 1983. Nuclear winter is not the fanciful conjecture of a few, but the result of a remarkable convergence among scientists throughout the world and representing such varied concerns as mass extinction in paleontology, the study of planetary atmospheres, the geology of impacts, atmospheric physics, and global climatic modelling. Rarely has any scientific study been subjected to such widespread scrutiny before publication.

Biological results are vastly more complicated and subject to uncertainty than the physical effects that yielded the basic model of nuclear winter. I will not, therefore, enumerate specific predictions. What we can say, virtually for certain, is that the biological impact will be severe, perhaps irreversibly disastrous (as in the mass extinctions of our geological record). Since plausible models of nuclear winter reduce light to 1% of current ambient levels, and depress summer temperatues to -40°C in continental interiors of mid latitudes, the biological effect can scarcely be mild. Admittedly, effects of this magnitude accompany one of the more severe versions of nuclear winter (but by no means the worst among plausible scenarios). Yet acceptable and traditional planning for disaster must base its preparations on scenarios at the severe end of reasonable prediction. Remember the Titanic.

Three general principles of biological systems engender the uncertainty of specific prediction while leading to the general conviction that biological effects of nuclear winter might be immediate and severe. First, the complexity of interactions. Biological systems contain more complex and interacting components than any other piece of nature. Impacts upon one species or local population may propagate up and down food chains and through ecosystems in waves of increasing severity. If we lose much oceanic phytoplankton through suppression of photosynthesis by low light levels of nuclear winter, we may impact the entire ecosystem of the sea (since the microscopic plankton lie at the base of marine food chains), with disastrous effects upon human fisheries.

Second, the small tolerance of certain biological systems, particularly those artificially maintained by human intervention. Some (though not all) biological systems are well buffered by evolutionary history against environmental fluctuations (though not necessarily to the unexperienced effects of nuclear winter). But many biological systems most crucial to human life, the agriculture of major ceral grains in particular, are artificially maintained by necessary, massive and continuous human input. These might collapse completely under the assault of nuclear winter. Most cereal fields are unstable monocultures, often grown at the edges of ecological possibility, made of genetically uniform stocks (therefore unusually susceptible to disease), and dependent upon inputs of fertilization and irrigation that would almost surely by cut off after nuclear exchange.

Third, synergisms, or, in technical parlance, "non-additive interactions." We cannot, in assessing the impact of disaster upon natural systems, simply add up the predictable effect upon each component separately in order to measure the response of the whole. Bad plus bad need not yield twice as bad, but often many times worse. The intense radiation of a nuclear war, for example, might produce by mutation a new and potent agent of microbial disease. The effect of such a vector might then be heightened by several other impacts of radiation: general weakness of organisms by radiation sickness and particular suppression of immune systems that might otherwise fight disease.

We must distinguish between two types, or scales, of biological effect for nuclear winter: the immediate increment of human suffering and long-term impacts upon ecosystems (including extinctions). Most uncertainties involve the second category of long-term effects, and these potential results are admittedly more spectacular. But effects in the first category -- immediate increment of human suffering -- are much clearer and more than enough in themselves to justify our deep concern.

Although long-term effects are so hard to predict, I might simply cite *in toto* the last section, labelled *Conclusions*, from the original paper written by 20 biologists and published as a companion piece to the original TTAPS report on nuclear winter.

> The predictions of climatic changes are quite robust, so that qualitatively the same types of stresses would ensue from a limited war of 500 MT or less in which cities were targeted as from a larger scale nuclear war of 10,000 MT. Essentially, all ecosystem support services would be severely impaired. We emphasize that survivors, at least in the Northern Hemisphere, would face extreme cold, water shortages, lack of food and fuel, heavy burdens of radiation and pollutants, disease, and severe psychological stress -- all in twilight or darkness.
>
> The possibility exists that the darkened skies and low temperatures would spread over the entire planet. Should this occur, a severe extinction event could ensue, leaving a highly modified and biologically depauperate Earth. Species extinction could be expected for most tropical plants and animals, and for most terrestrial vertebrates of north temperate regions, a large number of plants, and numerous freshwater and some marine organisms.
>
> It seems unlikely, however, that even in these circumstances, *Homo sapiens* would be forced to extinction immediately. Whether any people would be able to persist for long in the face of highly modified biological communities; novel climates; high levels of radiation; shattered

> agricultural, social, and economic systems; extraordinary psychological stresses; and a host of other difficulties is open to question. It is clear that the ecosystem effects alone resulting from a large-scale thermonuclear war could be enough to destroy the current civilization in at least the Northern Hemisphere. Coupled with the direct casualties of over 1 billion people, the combined intermediate and long-term effects of nuclear war suggest that eventually there might be no human survivors in the Northern Hemisphere. Furthermore, the scenario described here is by no means the most severe that could be imagined with present world nuclear arsenals and those contemplated for the near future. In any large-scale nuclear exchange between the superpowers, global environmental changes sufficient to cause the extinction of a major fraction of the plant and animal species on the Earth are likely. In that event, the possibility of the extinction of *Homo sapiens* cannot be excluded.

Sobering as these long-term possibilities may be, we need not venture beyond the immediate -- and much more clearly predictable -- increment in human suffering to seal our conviction that nuclear winter represents a great danger, heretofore unrecognized. The probable collapse of northern hemisphere agriculture in a crowded and hungry world is potential disaster enough.

The prospect of nuclear winter, however frightening, may at least (and at last) teach us that we are truly one world and that the result of nuclear war, for any one nation, could only be the most ultimately Pyrrhic of all "victories."

Mr. **Scheuer.** Congressman Valentine of North Carolina, who has just joined us, just poked me in the ribs with a pencil, just as you were giving your last sentence, and he said, "This is a heck of a panel we've got here." It is, indeed, a heck of a panel.

Congressman Tim Valentine of North Carolina has joined us, and our distinguished colleague from Rhode Island, Congresswoman Claudine Schneider, so we're beginning to show up in proper force.

Well, thank you very much, Dr. Gould.

Dr. Edward Teller, whom we will hear from next, is well known for his contributions to the Manhattan Project. He's a senior research fellow with the Hoover Institution and a physicist at the Lawrence Livermore Laboratory. His interest in chemical, molecular and nuclear physics and their applications to nuclear energy have led to publication of numerous books and articles, and to a large number of honorary degrees and awards, including the Einstein award.

Dr. Teller is a consultant to the President's Foreign Intelligence Advisory Board and a member of the Science Advisory Board to the U.S. Air Force.

We're delighted to have you here, Dr. Teller. We're aware of the fact that you came from the west coast, so you win the door prize for having come the furthest distance to our little hearing. Please proceed as you wish.

Incidentally, let me—let me say for all of you that your full remarks will be printed at this point in the record, so please proceed for approximately 10 minutes, Dr. Teller, and then I'm sure we'll all have some questions for all of you, and then we are going to allow some time for each of you to address questions to the other two members of the panel.

Please proceed.

Dr. **Teller.** Thank you very much. My peregrinations to Washington have not started yesterday; they have started 38½ years ago. For that time and longer, I have been worried, continuously worried, about problems much more severe, much more fateful than what is at all probable to result from the nuclear winter.

I have been worried about the necessary avoidance of a third world war, nuclear, biological, or otherwise, and so have you on Capitol Hill, and that is why I have spared no effort and why I have turned away from the subject I greatly prefer—pure theoretical physics. This was a matter of duty which I have served for decades, and served it, I may perhaps add, not always in the most popular fashion.

I have submitted to you a brief statement—it's available—together with an article in Nature in which I say in detail one very important thing that you must understand, and you can, and you will. The agreement between scientists that has been here claimed is similar to the agreement, with a slight exaggeration, that 2 and 2 make 4. If you make certain assumptions and stick them in the computer, that will be the result. If you vary your assumptions within reason, you get vastly different results.

Now, what we witness here is not unprecedented. In my long career, in worrying about these things, in talking about these things, I have lived through two other scares. One was the fallout scare, which predicted the end of the human race. Many of you remember the famous picture, "On the Beach."

Nothing is wrong with that picture. If you make the wrong assumptions, you get the wrong results. The danger of worldwide fallout is real, but the effects are negligible compared to the truly horrendous effects that will occur in the belligerent nations. Similar exaggerations have been committed in connection with the depletion of the ozone layer. Both these points have been amply discussed and both are now recognized for what they are: serious questions worthy of study, but not questions which greatly add to our imperative to work toward a world in which a third world war just will not occur.

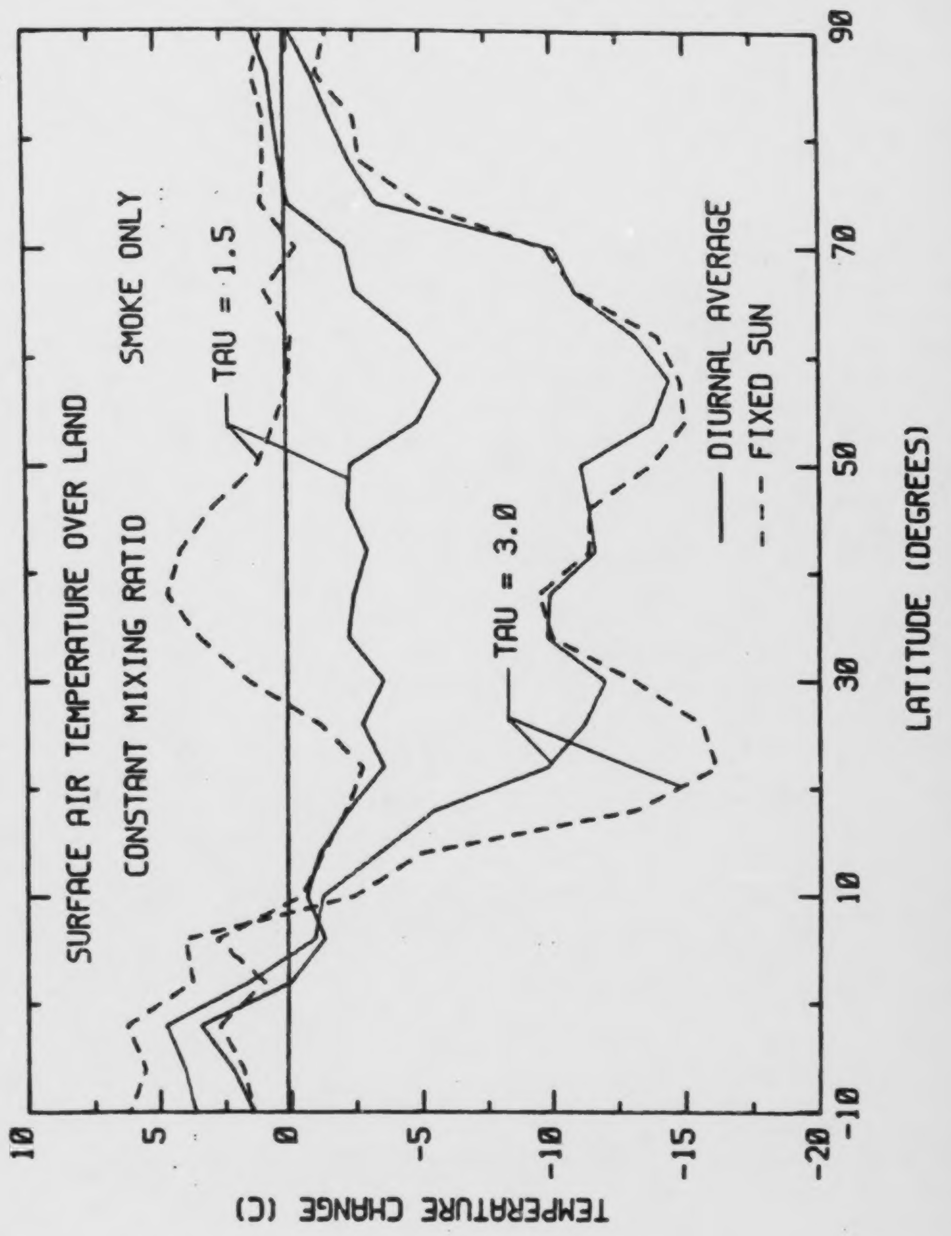
Now we hear that cry rise for at least a third time in connection with the nuclear winter, and this time, it is in a region where complete study, complete discussions are incomparably harder. We in Livermore have worked on it for years. We have not publicized our results because we are fully aware of their uncertainties, and indeed, the general interest which has now arisen has some good features. Our interest did not have to be recruited. It was already there.

But your interest in spending adequate funds to know the facts—on that, I think, the three of us are unanimous—that these facts must be brought out in the open and it is always more fruitful to emphasize the agreements between your witnesses than the disagreements.

Now, I would like to show you something about our limits about the dimensions of our ignorance about this problem, of what temperature changes, what climate changes may follow the widespread burnings. And incidentally, these burnings themselves are the direct reason for a great fraction of the billion deaths which may well follow a third world war.

May I please have the transparency.

[The viewgraph follows:]


SURFACE AIR TEMPERATURE OVER LAND
CONSTANT MIXING RATIO
SMOKE ONLY
TAU = 1.5
TAU = 3.0
DIURNAL AVERAGE
FIXED SUN
TEMPERATURE CHANGE (C)
LATITUDE (DEGREES)
10
5
0
-5
-10
-15
-20
-10
10
30
50
70
90

Dr. **Teller**. This is a picture from an unpublished paper. That paper has been presented at an international conference a few weeks ago and I will tell you what this picture shows. This picture tells us what temperature changes to expect on the basis of calculations of three people, Cess, Gates and Potter, from all over the United States, but unlike all other people, they not only made the usual assumptions, they also varied their assumptions and showed what the variations resulted in.

Will you please focus on a point which lies on the lower scale between 10 and 30. That means 10 degrees northern latitude to 30 degrees northern latitude and the picture tells you what happens between minus 10, which is 10 degrees southern latitude, and the North Pole, which is 90 degrees northern latitude.

For these latitudes there are plotted the average temperature changes. For instance, you see that somewhere around 15 degrees northern latitude, you can expect a temperature decrease by 15 degrees or a little less than 10 degrees according to the two lower curves. These are degrees Centigrade; in Fahrenheit, it would be a little less than double that figure.

The two curves, just to show a little different dimension to the whole calculation, have been made under two conditions. The dotted curve is a usual condition. You assume that the sun does not move; it stays fixed in the sky, and this has been assumed in all calculations so far, together with a number of other assumptions, like, for instance, the assumption that the smoke immediately rises to a point about 10 kilometers above the Earth surface—where the temperature is lowest—and stayed there.

We know that this will not happen for at least—for approximately 2 weeks, and what will happen within these 2 weeks, nobody knows. What we do know is that the smoke will encounter approximately 10,000 times as much water in the atmosphere and there will be plenty of opportunity that while the smoke is rising, it will be rained out by the wetness, the water which is already there.

Furthermore, these calculations show that in the tropics, the rain continues to fall, contrary to the conclusions of all other papers, which have put the smoke arbitrarily into a position where there is no moisture and where, therefore, there can be no rain. If you assume there will be no rainout, there will be no rainout and no calculation will change it.

Here, a chance was given for rainout and it did occur. The smoke assumed was the same as in the work by Turco and others, to which Dr. Sagan referred, and the values plotted, which are preliminary values, are average values over land areas which are the only areas where the temperatures change. For a long time, many weeks, a few months, the ocean temperatures will not change and therefore, the extinction of oceanic species is something of an even greater extrapolation than the rest.

But now I come to the important part of the diagram. You see on the top two more graphs. TTAPS assumed that the smoke that rains out, and the calculations they did make, not a calculation about the rainout of the smoke, but an assumption about the rainout of the smoke—maybe one-third of it rained out. If the remaining smoke is cut in half, and you repeat the calculation—and incidentally, in this model, the smoke was not put on top, but was mixed in with the air, as is the case after 10 days of the fire for which this calculation was performed—if you assume now that by the tenth day in the meantime, half the smoke is gone, you have half the smoke, then you see that depending whether you assume that the sun is fixed or the sun is moving, you may get a relatively small temperature decrease or a temperature increase.

In the worst case here calculated, which is not the worst case possible, you've got quite a bit less than the earlier calculations, partly or mostly because this gives the average temperature over a whole latitude—its, continental parts, because over the ocean there is no temperature change. If you cut the smoke in half—and estimates of the amount of smoke have been done by my good friend, Dr. Broyles, from Florida—he finds that the probable smoke emission varies all over the place, from less than one-tenth that has been assumed to a factor 1.5 greater than has been assumed. So one-half of the smoke that has been assumed is, by all means, within the possibilities—within the probabilities, and the effect is that you get a little warming, a little cooling. You don't even know which, whether it is warming or cooling.

We must assume the worst case if you only knew in today's dangerous world what the worst case is. I say war is the worst case. But I also say, that loss of our freedom compares to the dangers of war and I know that you have a broad enough view not to oversimplify these problems. I don't need the projection anymore.

I have a few concluding words to say. A number of people, for sake of simplicity, repeated the same calculations with the same assumptions and found the same results, which shows nothing except that our computing machines are working.

As soon as you change the assumptions within reason and closer to reason, the effect disappears. That does not mean that nuclear winter is uninteresting. We have asking for funds; we have been spending funds; and we have been trying and the work on better prediction has been started under my directorship in Livermore more than—more than 20 years ago, about 25 years ago. It has been taken up in Colorado by very excellent people.

These calculations have to be fully supported with the best of will, with the most elaborate methods, diligence, and money. You will get new ideas; you will get a more reliable picture, but for at least 3 years, there will be no conclusion except the one that war is already so bad that the probable cause will be with this catastrophe, as it was with fallout, as it was with the ozone layer.

To jump to premature conclusions, to allow people to talk about scientific agreement where there is none, that is, gentlemen, and ladies, not good for science, not good for politics, and that it is not good for politics is a more important thing. By pursuing calculations, we will not only be able to have a little more knowledge about nuclear winter; we will be able to predict weather, hopefully—very difficult and so far unsuccessful—except for 5 days in advance. We might be able to influence the climate and once that happens, we will have lost our last safe topic of conversation and it is a very serious question because the result may well be disagreement between nations on what should be done about influencing the climate.

Therefore, the research must be supported and must be supported on an international basis so that future possible conflicts should not be made even worse by misunderstandings. At least we should understand each other, and then, making the improbable assumption that homo sapiens is sapiens, there will be no third world war.

Now, please, I have here a note from one of my friends which I must read to you. Rich Wagner said that Sagan "grossly misrepresented" what he, Rich Wagner, said in his testimony—and give me the pertinent quote. Where is the pertinent quote?

Dr. SAGAN. I have it right here, Edward, if you'd like. [Laughter.]

Dr. TELLER. "In response to Senator Proxmire, assistant to the Secretary of Defense, Richard Wagner, said"—and this was in the course of a complicated exchange—"let me preface it"—and this is a remark of his—"by saying that my personal expectation is that after we do all this work, we will find that in most scenarios and in most combinations of the uncertainties of the variables, that there will be some sort of nuclear winter," and he emphasized that that was a personal expectation. It was in no sense a DOD position and he very extensively qualified his expectation, both before and after this particular statement, which he said was the closest that could possibly be construed to his stating that there would be a nuclear winter.

He said that he felt that a statement lifted out of context by Professor Sagan to the effect that "there would be a nuclear winter" was a gross misrepresentation of his position and of what he said to the Senate committee.

I hope I am excused for making it possible for my friend, Rich Wagner, to put his own words in his own way before you.

[NOTE:—The exchange between Senator Proxmire and Mr. Wagner may be found in "Effects of Nuclear War," a publication of the Joint Economic Committee (July 11-12, 1984).]

[The prepared statement of Dr. Teller follows:]

STATEMENT OF EDWARD TELLER

BEFORE THE

SUBCOMMITTEE ON NATURAL RESOURCES,
AGRICULTURE RESEARCH & ENVIRONMENT

SEPTEMBER 12, 1984

There is no more important political task today than to avoid a third world war if that is at all possible. In the first world war the casualties numbered 10 million; in the second, 50 million. The probable number in a third world war will lie between 100 million and a billion.

If there is a third world war, the use of nuclear weapons is highly probable. This has been taken into account in my estimate of casualties. The probable occurrences will indeed be horrible, but to predict the end of mankind or even the end of life on earth is an unwarranted exaggeration. Such predictions have proved false in connection with fallout and the depletion of the ozone layer which have been well publicized and thoroughly discussed in the past.

In December 1983 I appeared on a television program together with Carl Sagan, Paul Ehrlich, and by satellite with the Soviet Academician Sergei Kapitze. Dire and practically unqualified predictions were made about a nuclear winter by Sagan, and dire consequences were predicted by Ehrlich. Kaptiza expressed agreement. I stated that on the basis of quite preliminary results I would expect only one-third of the predicted effect, but these results are most premature; I can neither deny the occurrence of the full effect predicted by Sagan nor could I exclude the possibility that no observable changes would result. When the moderator asked Sergei Kapitza, he replied that in the Soviet

Union no such differences of opinion existed since they all agreed that the results would depend on the assumptions.

In the meantime, more calculations have been performed which indeed bear out the statement that effects are most uncertain. As an example, I submit a figure from a paper of Cess, Potter, and Gates, in which the temperature changes averaged over the continental areas between the latitudes 10°S to 90°N are shown for four cases. In two cases, the assumed smoke emission is similar to that treated by Turco and others (including Sagan). In this calculation, the effect of diurnal changing of the position of the sun was taken into account, a circumstance neglected in previous papers. A second pair of curves show very much smaller changes, in some cases even a temperature increase. These calculations assumed that only half of the smoke is present. Since rain is apt to precipitate a considerable amount of smoke, one cannot say which if any of these pairs of curves is more realistic.

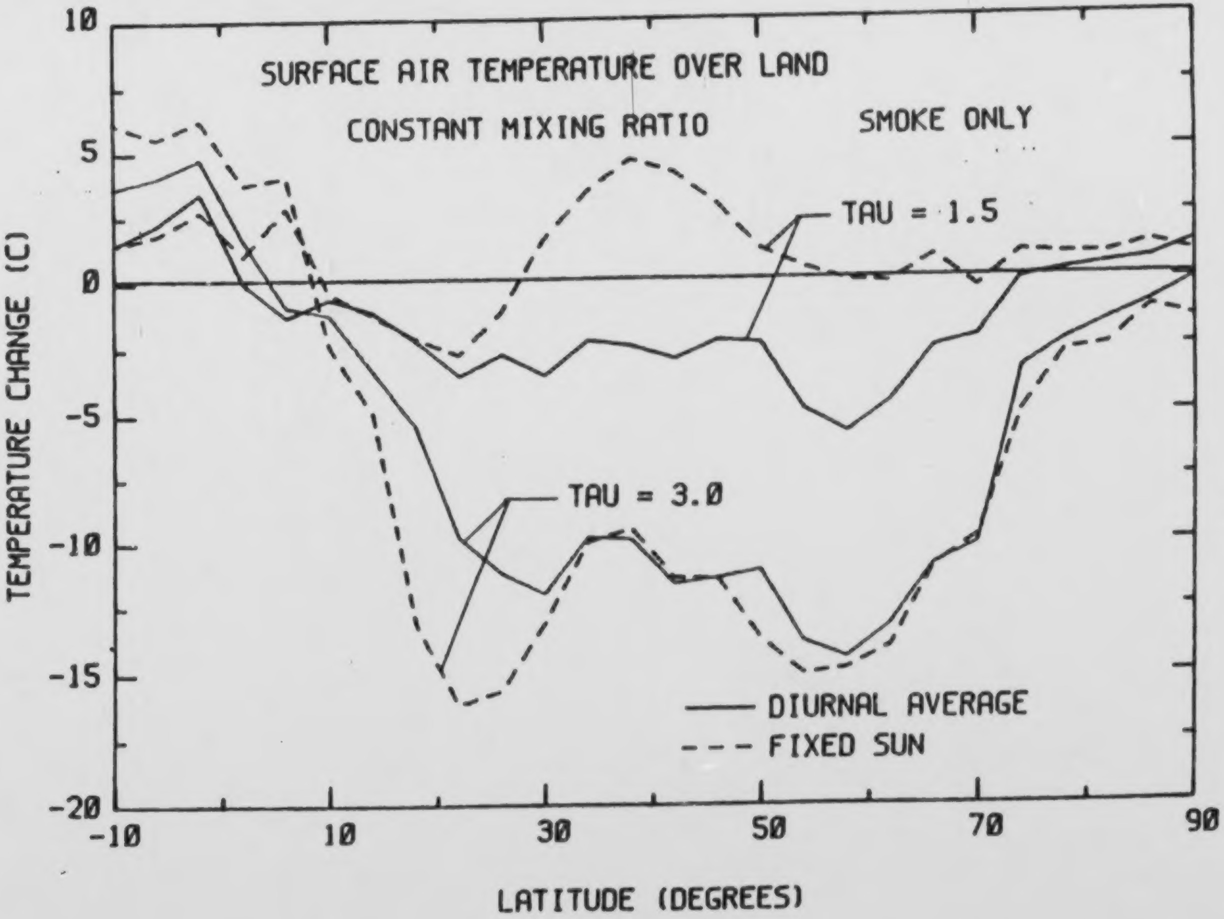
In a recent publication in Nature, which I submit, numerous assumptions have been listed, all of which are apt to change the temperature effects due to smoke emission. It is clear that information about "nuclear winter" remains quite inconclusive.

It has been recommended that national expenditures on numeric atmospheric modeling to be carried out at NCAR, Lawrence Livermore National Laboratory, and other places should be increased by an annual amount of $10 million. Even so, it will take several years before conclusive results are to be expected.

The question of "nuclear winter" is only a part of the much bigger and most important problem of understanding the processes in our atmosphere, ranging from local effects and practical consequences such as acid rain, all the way to worldwide climate and its changes. Understanding in this field could lead in the long run to improved weather predictions or even climate modification, though this will require not only calculations but better weather observation as well. It seems to me clear that this difficult problem, where success has eluded us for two decades, is a national responsibility.

I also believe that the work should be performed in collaboration with all nations. Eventually, weather (or climate) modifications through the use of trigger effects may have to be envisaged. In peacetime these could lead to positive results of great importance if and only if accompanied by international understanding. Otherwise, such modifications might give rise to dangerous international frictions. By common work and avoidance of misunderstandings, these dangers could be reduced.

In the past decades, great efforts have been made toward a better understanding of weather. The greatest importance of discussion of "nuclear winter" may turn out not to be connected with the dangers which today are widely proclaimed, but rather with the impetus that meteorological research may receive.


SURFACE AIR TEMPERATURE OVER LAND
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TAU = 1.5
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FIXED SUN
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LATITUDE (DEGREES)

Widespread after-effects of nuclear war

from Edward Teller

Radioactive fallout and depletion of the ozone layer, once believed catastrophic consequences of nuclear war, are now proved unimportant in comparison to immediate war damage. Today, "nuclear winter" is claimed to have apocalyptic effects. Uncertainties in massive smoke production and in meteorological phenomena give reason to doubt this conclusion.

CORRECT identification of danger is essential to intelligent action. Scientific knowledge of the after-effects of a nuclear war — fallout, ozone layer depletion and climatic effects — is of great importance in making political decisions. Early fears concerning two of these, fallout and ozone depletion, turned out to be exaggerated. A third, the fear of climatic changes due to smoke and dust, is under active discussion now. The study by Turco *et al.* is an early contribution to the question[1]. The preliminary and uncertain nature of their findings deserves clarification.

Fallout

The consequences of war-engendered fallout on non-combatant nations were the first to receive widespread popular attention. During the 1956 Presidential campaign, Adlai Stevenson raised the problem of worldwide fallout in an arresting manner. In 1957, a book, *On the Beach*, and its subsequent movie version popularized and perpetuated the belief that the effects of fallout would endanger, and probably extinguish, all human life[2].

In 1975, the US National Accademy of Sciences issued a report in which the estimates of war-produced worldwide fallout were so low as to have insignificant biological consequences[3]. However, estimates used in the study were scaled from larger nuclear weapons tests and, therefore, were not representative. Actual weapons tests avoided atmospheric conditions where rainfall was expected, and were not carried out in middle latitudes. Because of their size, a larger fraction of radioactive products from the tests was injected into the stratosphere than would be from current weapons and, because of the longer residence time in the stratosphere, the radioactivity of fallout from a nuclear war was underestimated.

The best current calculations, made at Lawrence Livermore National Laboratory (LLNL), suggest that global-scale fallout will expose people in the non-belligerent countries in the Northern 30 to 70 degree latitudes to an average external dose of 20 rem — a total dose delivered over 50 years[4]. It is important to note that this estimate holds on the average. Vagaries of weather, particularly of rainfall, can concentrate fallout in large but limited areas called hot spots, where the total dose values in non-belligerent countries could be as high as 250 rems[4]. (The assignment of these doses does not take into account the shielding afforded by houses, which would reduce the radiation received by up to one-half.)

A given radiation dose received over a long period is generally less harmful than the same radiation dose received in an short time, because of continual biological repair[5,6]. The formula for slow dose rates in current use suggests that 90 percent of the damage is repaired at the rate of 2.5 per cent per day[5]. An acute dose of 100 rem or less does not cause appreciable radiation sickness. When the biological recovery formula is applied, a dose as high as 250 rem from worldwide fallout is built up at a rate so slow that it would not produce significant casualties.

Inclusion of radioactive elements in the food chains might, on the average, increase these estimates by a factor of two[4]. Simple precautions based on generally held knowledge about fallout, such as that offered in public schools in the Soviet Union, could sharply limit this danger. The contrast between the long-term danger of fallout to the worldwide population and the great immediate dangers in combatant countries is extremely marked.

The worst case of fallout would occur if all nuclear reactors and all used reactor fuel elements were subjected to explosions violent enough to disperse their radioactive contents. Under these conditions, the 20 rem average dose and the 250 rem "hot spot" dose may need to be multiplied by a factor of about eight[4]. Fallout in the non-belligerent northern hemisphere countries could then be a considerable danger. Vaporization and dispersion of reactor radioactivity is not easily accomplished nor does it appear to serve any important military purpose. It is therefore unlikely to occur. Early underground disposal of wastes would greatly diminish this danger.

Thus, there is almost no likelihood that fallout outside the belligerent nations (with the exception of regions close to the belligerents) would have a major damaging effect. Even in the belligerent countries, fallout would have less important effects than the immediate effects of fire and blast if the most elementary civil defence measures were exercised. Fallout is an example of a consequence that further study has shown to be far less important than originally feared.

Ozone layer damage

In the 1970s, there was concern about the possible effects of a nuclear conflict on the ozone layer[3,7]. The small amounts of ozone present in the stratosphere play an important role in shielding the Earth from ultraviolet radiation. Large nuclear explosions propel the contents of their fireballs, including the molecules NO and NO_2 (collectively referred to as NO_x), into the high atmosphere where they react with ozone, eventually converting ozone to oxygen molecules (O_2).

If injected in sufficient quantity at high altitude, the NO_x could deplete the ozone layer significantly. Ozone molecules are steadily regenerated by solar radiation, but the NO_x residue from large nuclear explosions could reduce the effective thickness of the ozone layer by an average of 30 to 40 per cent for a period of a year or two[8,9]. (For purposes of comparison, the effective thickness of the ozone layer during summer is about 20 percent less over Miami than Seattle.) Complete recovery would take several more years[9].

Assuming the explosion of thousands of megaton weapons, the calculated diminution of the ozone layer would give rise to increased serious sunburn immediately and to an increased incidence of skin cancer over an extended time. These primary effects, like the possibility of eye damage, could be countered with simple precautions. A secondary concern is that ozone depletion and the consequent increase in ultraviolet radiation would destroy ultraviolet-sensitive plants or plankton species, and would harm early springtime plant growth, with important effects on ecosystem viability[10].

Since, in middle latitudes, observed natural variations of the ozone column are comparable with the predicted effects of a nuclear war with megaton weapons, the changes are not likely to be highly significant[11]. The most pertinent consideration, however, is that the present US

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arsenal has few nuclear explosives with the great yield that is a necessary precondition for depletion of the ozone layer. The same trend toward smaller, more accurately aimed and less costly weapons also has been adopted with some delay by the Soviet Union.

In conclusion, problems related to a weakening of the ozone layer seem manageable, and with the rapid elimination of weapons large enough to cause ozone layer damage, the probability of serious ozone layer depletion is dropping significantly.

Effects of dust

In the mid 1960s, the climatic effect of dust raised by multiple nuclear blasts became a concern at Lawrence Livermore National Laboratory. (Unfortunately, this early work by R.G. Gutmacher and G.H. Higgins is still classified.) Dust in the post-attack atmosphere would tend to reduce solar radiation received at the surface of the Earth. If this reduction were sufficiently large and prolonged, the hemispheric temperature would be lowered.

The effects produced by blast-lofted dust from nuclear explosions can be expected to be analogous to those produced by dust spewed into the atmosphere by volcanic eruptions. Annual growth rings in bristlecone pine trees show the effects of early frost, and these changes are correlated with large volcanic eruptions that distributed dust in the upper atmosphere[12]. Comparing the historic volcanic events with annual growth rings offers a rough measure of the relationship between dust and worldwide temperature[3].

The quantity of small particles in the dust raised by a large scale war is comparable with that produced in the largest volcanic eruptions. Recent estimates of the mass of small dust particles that would be lofted into the stratosphere in the event of a nuclear war are based on scanty information. Review and analysis of old air filter samples and recent tests involving large amounts of high explosives may provide a more reliable basis for calculations.

The most probable conclusion is that the atmospheric effects from war-generated dust would be noticeable but by no means severe on a hemispheric scale.

Effects of smoke

In 1982, Crutzen and Birks proposed that smoke particles from forest fires produced by a nuclear war would give rise to a much more serious effect than dust. Smoke absorbs sunlight as well as scattering it[13]. In 1983, Turco *et al.* argued that smoke generated by fires in bombed cities or oil refineries would produce even greater effects than those from the forest fires[1]. In discussing these results, some scientists have created the impression, aided by a short movie depicting the postulated effects, that smoke from fires ignited by nuclear explosions and, to a lesser extent, the dust raised by a nuclear exchange would bring about what is now known as "nuclear winter"[14].

The theory of a severe nuclear winter depends on the assumption that a large quantity of smoke will be emitted by burning cities and forests and will be distributed in the troposphere. Such smoke-laden air, heated by sunlight, could raise the temperature at the tropopause from approximately -50° to -60° C to about 5° C. The surface temperatures of the continents in the Northern Hemisphere between the latitudes of 30° and 70° might drop to about -30° C because of the absorption and scattering effect of the smoke.

A large quantity of smoke at high altitudes would produce an extremely massive inversion, a state in which the temperature increases, rather than decreases, with altitude. In regions of inversion, rising air masses lose their buoyancy, so water condensation and rain is suppressed. Thus, smoke would persist in the upper atmosphere, shielding the Earth's surface from sunlight. This situation could persist for long periods of time, and the resulting temperature change would damage all life in the underlying region. The argument, as continued by Sagan, holds that smoke may well be distributed over the entire globe and that the survival of the human race could be endangered. Although the findings of Turco *et al.* are inconclusive, Sagan calls them scientifically robust[14].

Examination of the possibility of nuclear winter differs from ascertaining fallout and ozone layer depletion because it depends on meteorological phenomena that involve much more detailed and complex considerations and calculations. Several important meteorological processes are inadequately understood, and the bases for smoke estimation are very uncertain. Computer modelling sufficiently detailed and refined to handle all the various pertinent factors is not yet available.

It would take about two weeks for the smoke to disperse over wide areas. Turco *et al.* do not consider[1] in sufficient detail the abnormal mechanisms that may be operating during this period which could sharply decrease the amount of smoke available. There is inadequate quantitative allowance for the effects of several major meteorological phenomena in the prediction of the nuclear winter, and the bases used for smoke estimation are most uncertain.

The average tropospheric residence time of fine dust particles, such as those containing radioactivity, varies between one and three weeks[4]. The average residence time of water vapour in the atmosphere is little longer than a week[15]. Studies of the continuing discharge rates of man-made and natural smoke, and observations of the average amount of smoke found in the atmosphere, suggest that smoke may have an atmospheric residence time of a week or less[16].

Under all atmospheric conditions, water is the agent largely responsible for cleansing the atmosphere of smoke. Turco *et al.* estimate that 225 million tons of smoke particles (2.25×10^{14} grams) would be emitted in their 5,000 megaton baseline war[1]. A comparison between this weight of smoke and the weight of the water (droplets and vapour) in the northern latitudes between 30 and 70° shows that the water outweighs the smoke by a factor of ten thousand. The average lifetime of a water molecule in the atmosphere is little more than one week. So, in ten days, before the widespread smoke-associated cooling effect is established, a mass of water at least a few thousand times greater than the total mass of war-engendered smoke will rain out of the atmosphere. Turco *et al.* estimate that a factor of three or four of the smoke (depending on detailed conditions) will be removed by rainout in the fourteen day period.

The highly relevant question of how much smoke will remain aloft after two weeks of rainout is completely unanswered because it depends on the relative altitudes of water and smoke, on alterations in scavenging processes, on latitudinal variations and on various other factors. Two studies suggest specific cleansing factors.

The capping clouds which regularly appear in the smoke plumes above big fires are produced by condensed moisture that forms droplets too small to develop into rain. In one observation made for a US Environmental Protection Agency 1983 report (preprint, University of Washington, Seattle), L.F. Radke *et al.* measured the particle size distribution for smoke following two different paths, one through the cloud and one below it. A comparison of these two size distributions can be interpreted to say that the cloud reduced by a factor 10 the number of small smoke particles between one-tenth and one-half micron in size. The effect would be large because most of the particles would pass through the cloud. Unfortunately, this experiment has not been repeated for lack of funds. More experiments are now being planned.

Changes produced by the capping cloud may result from each of the water droplets trapping many small smoke particles. Upon subsequent evaporation of the water droplets, these particles are agglomerated into bigger units. In addition, Hanel observed that aerosols increase in size if they are exposed to air in which the relative humidity exceeds 90 per cent[17]. Increasing the sizes of the particles reduces their number in the range where they are most effective in absorbing and scattering the sunlight. Larger smoke particles also rain out and fall more rapidly. Thus, at the very origin of smoke generation, the particles already may be prepared for more rapid deposition.

The nuclear winter mechanism for the abrupt cooling of the Earth's surface and the lower troposphere is effective only over land. Over the oceans, the surface water is continually supplied with heat from below. For periods of many months, the temperature at the ocean surface would remain essentially unchanged.

The Turco *et al.* model for predicting nuclear winter did not include the effects of oceans or winds in a quantitative manner[1]. The National Center for Atmospheric Research (NCAR) uses a somewhat more realistic model of the atmosphere in that it includes oceans and winds[18]. In the NCAR model, the extent of the temperature reduction is lower by a factor two to ten (depending on the season) than in the Turco *et al.* study.

However, the NCAR model still postulates that the injected smoke layer appears instantaneously at all temperate zone longitudes. Furthermore, the NCAR model postulates that solar radiation is absorbed by the smoke layer as though the layer were fixed in its longitudinal position and concentration. This postulate ignores the motion of the smoke produced by convection processes related to natural induced air flow. Finally, in the absence of a usable model, the NCAR study postponed a consideration of the most important factor of rainout. While the NCAR study is the most elaborate calculation yet produced, it does not provide estimates that can be considered final, even in an approximate sense.

If a nuclear winter were to begin, unusually great temperature differences would be established between continents and oceans. This results in increased storms along the eastern coasts of the continents, with consequent mixing of air from high and low levels of the troposphere. Air from lower altitudes has a higher moisture content which is conducive to rainout. The storms are mentioned by Turco *et al.* but not taken into account in the calculation of particle scavenging[1].

The warm wet air over the oceans might rise only to a fraction of the postulated stable altitude of the smoke layer. It is well-known, however, that storms and associated turbulent air quite often extend well above the region of the original source of the storm and may transport moisture up to the tropopause. If the rain removed smoke from one area while leaving it untouched in another, the smoke layer would be patchy. The obstruction of light is most effective when smoke is well spread. The hemispheric light reduction would decrease as patchiness increased.

The patchiness of smoke, in turn, could bring about further large temperature differences which will further drive the atmospheric processes that rain out more smoke. In this case, rainout of large smoke layers might proceed in an accelerating fashion.

Some smoke particles, particularly those from oil fires, absorb light strongly. At first these particles may be water-repellent, as Turco *et al.* suggest. This property changes after relatively brief exposure (24 hours) to natural oxidizing agents in the atmosphere. Such agents are likely to persist, at the very least, in the relatively clear patches intermixed with the smoke. Pure graphite is water repellent, but smoke usually consists of graphitic particles covered by organic material. Alternatively, large particles would act as condensation nuclei even if hygrophobic. Radke's observation suggests that wood fires produce water-attracting particles even initially. Therefore, there is little reason to expect that rainout of all types of smoke particles would not occur.

Capping cloud created by a forest fire at Reno, Nevada in July 1984. The photograph shows the smoke plume, the entrainment of the smoke into the central portion of the capping cloud, and the de-entrainment of the smoke aerosol from the lower portions of the capping cloud. (Photo by John Hallet of the University of Nevada Desert Research Institute.)

In conclusion, there is no obvious reason why large quantities of smoke particles should have a long residence time in the atmosphere. The calculations associated with the nuclear winter do not include major cleansing effects of water vapour which are themselves smoke-induced or the influence of the oceans and winds during the time needed for spreading the smoke world-wide.

A recent detailed study by A.A. Broyles, based on observations of forest fires and considering the proper modifications pertinent to a discussion of burning cities, proposes that the upper limit of smoke that might be emitted in a nuclear war is 360 million tons while the lower limit is 15 million tons[19]. These limits are not rigorous; somewhat higher or lower figures are possible. However, the Turco *et al.* estimate for their baseline war producing 225 million tons is in the upper range.

The uncertainties associated with the amount of smoke that would be emitted are extremely numerous. The ratio of wood burned to smoke emitted depends on many factors, including moisture content, the temperature of the air surrounding the fire, the manner in which the wood is packed and the accessibility of oxygen. The last two factors depend respectively on the size of the object burning and on the wind velocity.

Estimates of the quantity of smoke generated are based on assumption that the amount of smoke is proportional to the ratio of the weight of the smoke emitted to the weight of the fuel burned. The measured smoke emission factor presented in one forestry report ranges from 0.0025 to 0.063 for wood[20]. Measurements made at Georgia Technical Institute give values ranging from less than 0.01 to 0.2 for plastics[21]. There is some possibility that large urban fires may provide sufficient heating reinforcement among burning components to consume even more of the smoke that is indicated by these numbers so that even lower values are applicable.

Estimates of the quantity of smoke also depend on the area burned, which in turn depends on many factors including the radiant energy flux required to produce ignition, atmospheric transmittance and topography. Estimates of the density of fuel in the areas burned also involve a large factor of uncertainty. The amount of wood in forests is usually considered to vary between 0.5 and 10 kilograms per square metre[22]; the corresponding values are between 20 and 200 $\mathrm{kg\ m^{-2}}$ in cities[23-25].

In cities with the higher fuel density

values, fire storms are possible. Fire storms which loft smoke to very high altitudes are relatively rare events, apparently dependent on the presence of dense fuel and particular meteorological conditions under which practically all available oxygen is consumed. The possibility that firestorms may loft smoke into the stratosphere cannot be excluded, but has never been observed. Turco *et al.* assume that only 5 percent of the smoke produced is due to firestorms[1]. A great deal of variability exists, and at present, there is no reliable basis for large scale estimates of smoke emission from burning forests and cities.

Smoke generated by burning petroleum products, rubber and plastics tends to absorb light more strongly than the smoke from burning wood. The predominant fuel in cities, at least 95 percent, seems to be wood and paper products[23,24]. The strength of light absorption of city smoke is critically dependent on the proportion of petroleum products, plastics and rubber present. This uncertainty strongly influences possible temperature changes.

Petroleum refineries could provide a total of 150 million tons (1.5×10^{14} grams) of fuel in the United States[26]. The weight of smoke would be about 15 million tons. Much of it would contain sulphur oxides, and less than 10 per cent is apt to consist of strongly absorbing carbonaceous particles. Oil found or stored underground is not apt to be ignited. Thus, the strongly absorbing carbon-containing smoke from this source is small in quantity.

Another major uncertainty connected with the properties of smoke is based on an inability to predict how a war would be conducted. If only purely military targets were attacked with relatively small bombs, the amount of smoke generated would be much lower than that required for a nuclear winter, and the argument for the unavoidability of a nuclear winter would lose all force. Because of the trend toward more accurate, lower-yield missiles, indiscriminate damage — the source of great quantitites of smoke — is far less likely. The deployment of anti-ballistic missile defenses would reduce further fire and smoke.

Conclusions

During the two-week period required to establish the full effects of a nuclear winter, the water in the atmosphere, ten thousand times greater in weight than the postulated emitted smoke, most probably will rain out. This alone could reduce the smoke content at low altitudes manyfold. Other weather phenomena, enhanced by the patchiness of the smoke and the temperature differences between land and ocean, will serve to bring smoke from the upper levels of the troposphere to the lower, whence it can be removed. The immediate coagulation effect of capping clouds on the smoke is unknown, but it might reduce the small smoke particles emitted (which are the most dangerous) tenfold. The targets that would be attacked are uncertain. The proportions of highly light-absorbent smoke that would be emitted are also unknown. Complex factors such as fuel density, moisture content, air temperature and other properties related to smoke emission make current estimates unreliable. The associated effects of each of these uncertainties on temperature change tend to decrease the amount of smoke retained in the atmosphere. The effects of these uncertainties are large enough that revising a few of the smoke estimates and including a few meteorological effects invalidates the occurrence of a severe nuclear winter.

Given the uncertainties and omissions in the theory on which nuclear winter is based, the concept of a severe climatic change must be considered dubious rather than robust. Nonetheless, the *possibility* of nuclear winter has not been excluded.

The probability that war-engendered smoke and dust would reduce the temperature by at least one-tenth the number of degrees that Turco *et al.* predict, is obviously much greater than the probability of the occurrence of extreme temperature changes. A decrease of 5° or 6° C between northern latitudes 30° to 70° during summer, rather than the predicted 50° or 60° C, could still lead to widespread failure of harvests and famine.

Therefore, there is every reason to undertake the difficult task of arriving at more realistic predictions. More funds should be allocated for experiments to sample fire plumes and to determine how emissions scale with the size and type of fire. Greater amounts of money, carefully spent on atmospheric modelling and experiments, would accelerate resolution of the basic questions regarding nuclear winter.

From Biblical times to the present written records testify to times of food shortage from causes ranging from volcanic activity to mankind's folly. The amount of suffering that would be produced today by the failure of a single year's harvest is horrifying to consider. Extensive food storage could decrease greatly the risk of famine and could be easily accomplished in the United States, and in many other nations. The usefulness of such storage is unquestionable.

Highly speculative theories of worldwide destruction — even the end of life on Earth — used as a call for a particular kind of political action serve neither the good reputation of science nor dispassionate political thought. Informing the general public about the reliability, unreliability or incomplete nature of such studies seems an important responsibility, for only then can decisions affecting the well-being of Western societies be made on an intelligent basis.

I thank the scientists in the LLNL Atmospheric Sciences Division — Joseph B. Knox, Michael C. MacCracken, Frederick M. Luther, and Joyce E. Penner — for the research on which my main conclusions are based and for their comments on this paper. Particular thanks are due Professor Arthur A. Broyles, University of Florida. Finally I thank the Hoover Institution, Stanford, California, for continuing editorial support. This work was performed under the auspices of the US Department of Energy under contract W-7405-Eng-48. The views and opinions are nevertheless those of the author alone, and the usual US government disclaimer of legal responsibility, explicit or implied, should be understood as accompanying this article.

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Mr. SCHEUER. Thank you very much, Dr. Teller.

Before we proceed with the questions from the panel, would either Dr. Sagan or Dr. Gould or both like to respond briefly to Dr. Teller?

Dr. SAGAN. I would like to, Mr. Chairman, if I may. There—it's clear that on the fundamental question before this committee about support for further work on the atmospheric and climaticological aspects of nuclear war, there seems to be good agreement. Dr. Teller has a different view of the facts than I do. I'd be happy to spend a few moments explaining why the idea of massive smoke injections without significant rainout is not an assumption but a plausibility. I have some pictures to show, but I don't think that's the most useful use of the time of this committee. I'd be happy to do it if you'd like.

On the remark that Dr. Teller just made about "gross misrepresentation" of Mr. Wagner's remarks, I was at that hearing of the Joint Economic Committee, as were many members of the press and other scientists, and permit me to read—to quote—this is a United Press International long article that appeared 10 days after the meeting, which—let me read a few paragraphs.

"The theory that nuclear war could ignite a climate disaster and create a nuclear winter, possibly freezing out mankind"—that's UPI talking—"has forced the Reagan administration to begin its own cautious study of the issue. Nine months after a group of scientists announced its findings based on mathematical calculations, the congressional committee gave public life to the conclusions and the administration testified officially that it did not know whether a nuclear war could bring on a manmade ice age.

"Unofficially, the Assistant Defense Secretary"—it's not an exact statement of his title—"of Atomic Energy, Richard Wagner, Jr., told the Joint Economics Committee on July 12: 'There will be a nuclear winter.' "

Let me quote from another source, almost always sympathetic to the Department of Defense, the Defense Daily, of July 13: "Pentagon official concedes likelihood of nuclear winter." It's a front-page headline. "Richard L. Wagner, Jr., Assistant to Defense Secretary Caspar Weinberger for Atomic Energy Matters, conceded yesterday that he expects that 'there would be a nuclear winter' if there were a nuclear war between the United States and the Soviet Union, even in a low-exchange scenario."

Let me say, however, that it doesn't matter what the Department of Defense's views are on the likelihood or unlikelihood as long as they're willing to support the studies. [Laughter.]

There is one other remark I'd like to make about the question of funding and that's the following: The work that is proposed to be done has been outlined—you will hear from him in a little bit—by Dr. Alan Hecht of NOAA, whose responsibilities are in climate and atmospheres. His charge did not involve studying the biological consequences, so there is, in the way things now seem to be unfolding, an important gap in the proposed funding. That is, that there will be support for a wide range of studies of fires and new climatic models, massive general circulation model calculations and so on, which is all to the good, but the present plan largely for administrative and bureaucratic reasons has—has not proposed to address the biological consequences.

Now, this can be done in—without prejudging the results of the atmospheric and climatic results by considering the consequences for a wide range of possible scenarios. In just the same way, consequences for policy and doctrine can be done by considering a wide range of possible consequences and I would urge the committee to urge the appropriate officials to add serious studies, both laboratory and field work and theoretical work, on the biological consequences of a wide range of possible nuclear winters.

One final remark just now, and that is: Dr. Teller says that he thinks that the effect might only be a few degrees and, therefore—I'm not quoting exactly—not——

Dr. **Teller**. You never do.

Dr. **Sagan** [continuing]. Not much to worry about. I'll resist that. [Laughter.]

The idea that a few degrees, say a 5-degree temperature decline for a period of months, is not much to worry about is a curious conclusion because such a temperature decline, quite apart from the massive radioactivity and toxic gases and other consequences of a nuclear war, would almost certainly be sufficient to destroy, as Dr. Gould stressed, agriculture throughout the northern midlatitudes where the war would presumably be fought, and that is the breadbasket of the world.

So the consequences of even a small nuclear winter can be profound and devastating. It does not have to be tens of degrees for it to be an unprecedented human disaster.

I'm sure I'll have both motivation and opportunity to make further comments later.

Dr. **Teller**. Mr. Chairman, may I very briefly respond to this? First, I wish to have quotes from Rich Wagner and from the Congressional Record, not from the press. Second, if you read the end of my major article, you will find there the statement that small temperature decreases—maybe one-tenth of what has been predicted—could have a serious effect on the agriculture, and I, therefore, recommend, and I do recommend that food storage be given serious consideration.

Dr. **Sagan**. For everybody on the planet?

Dr. **Teller**. The statement—wait a moment—the statement that I take small temperature changes lightly is simply not true and that has been printed before the remark of Mr. Sagan. Furthermore, he interjected "for everybody." The answer is, for the United States, it would be easy; for many others, it would be more difficult, but using methods like keeping down pests by irradiation, by that point alone, one could, in the Third World, increase the food supply by 20 percent.

That all these are serious questions I have never denied, and on that point, we agree and the imputation that by showing the limits and the dimensions of our ignorance, I have expressed no interest or negligible effects is directly contrary to my statements.

Dr. **Sagan**. I thought I heard Dr. Teller say in his testimony that a few degrees would not be too much to worry about. If that is not what he's said, I'm delighted at our agreement.

Dr. **Teller**. Be delighted. [Laughter.]

Mr. SCHEUER. We can all share in your delight, Mr. Sagan. [Laughter.]

Dr. GOULD. I just have a small and simple-minded comment. This is my first appearance in this august institution, so I'm not fully acquainted with its ways, but I am amazed to see how many different manners there are of saying pretty much the same thing. From my perhaps not sufficiently politically oriented perspective, this little contretemps about what Mr. Wagner did or did not say seemed to be saying the same thing. One, it was an official DOD position; the other one, just his personal opinion that nuclear winter is going to happen, it seems to me does say that he thinks nuclear winter is going to happen.

That's enough for me. It's an interesting statement. As to the chart that Dr. Teller put up, well, it's what—and I'm glad he agrees with it—one of his very plausible scenarios had a 10- to 15-Centigrade temperature decrease extending from—right from the tropical areas where, in fact, those temperature decreases are most serious because of the ecological tolerances of tropical species and their geographical ranges are so much smaller than temperate species, extending right up to the high midlatitudes where we all dwell is a disaster of the same order that we've been discussing and that emerges as a plausible scenario.

So although we have different ways of saying things which are in part consequences of our well known political attitudes, I sense a great measure of agreement among all of us and I just want to reiterate that that's a good thing.

Mr. SCHEUER. As a contribution to the serenity of the discourse, I'm going to provide each one of you with a transcript of the testimony of that day's hearing before the Joint Economic Committee on which I serve, and if any of you want to add a word or two about the testimony of the representative of the Defense Department, we'll hold the record open. It may not be necessary, but if any of you want to do that, we'll provide you with the printed testimony before that committee and if—and any comments you may have.

Dr. Teller, let me ask you this: You seem to feel that while the more cataclysmic and catastrophic variants on the whole scheme of possible effects of nuclear winter are not likely, you seem to think they are at least possible and that some severe climatological results are possible. If you had been a member of that famous team of TTAPS and made it TTTAPS: No. 1, how would you have done it differently; and No. 2, what would your comments be on how we should proceed from here on in to do elaboration of research on the fallout to our planet of nuclear—not only of nuclear winter resulting from a nuclear exchange, but perhaps other kinds of fallouts.

I frankly am a little bit astonished, to use your phrase, I'm a little bit astonished that four decades after the first nuclear explosion on Earth, we are finding in the last 12 months a whole new order of magnitude of devastation and danger to the human species, as well as biological effects all over the world. Why did it take four decades for us to find that out, and are there other things that we should be investigating, which we haven't developed?

And I would like—after Dr. Teller has finished—to ask all of you how would you alter or amend the current research design into the effects or fallout of nuclear war, not only further to define and more narrowly to describe—accurately to describe the effects and dangers of nuclear winter, but perhaps other things.

Do we have to take another four decades to find that there's a comparable or even greater risk to the survival of life on this planet that we hadn't thought about or hadn't stumbled onto for the first four decades? How could our scientific community not have come upon this and evaluated it and—and conducted serious scientific research before the end of the 39th year after Hiroshima?

How would you do it differently than we're doing it now? How would you improve the research design, Dr. Teller, and I'll ask the same—I hope the other two witnesses will answer the same question.

Dr. **Teller**. I have not signed that paper. Neither would I have signed it, or any modification of it, at that time. I would like to answer, and for a decent answer, I need a long time. I know you are busy and I'll try to be short.

Mr. **Scheuer**. Let me interrupt you at this point. This subject, as I said before, is of such transcendental importance that we don't want to limit any of you because our time today is limited. We will hold the record open and if you wish to address additional remarks to us, just prepare them, send them in, we'll hold the record open for 10 or 12 days and if you wish another couple of days, let us know.

We don't wish the shortage of time to be a limitation on you in terms of giving us your best wisdom, any of the three of you.

Excuse me, go ahead, Dr. Teller.

Dr. **Teller**. I would like to start by answering your most important question. That has occurred to me, that troubles me and troubled me for decades before the publication of the TTAPS report.

In 1958, I became director of the Lawrence Livermore National Laboratory. One of my actions was to initiate through an exceedingly talented computer expert, Chuck Leath, an effort on weather calculations for which we had the numerical equipment. Without that, and without the work of 20 years to try to predict weather, all this discussion could not have taken place.

If you wish, unknowingly, I foresaw a great potential interest and duty in that direction. We worked away on it, without success in predicting weather for more than 5 years—5 days.

I believe many more ideas have to be developed and much better computing machines and the computing machines and observations are improving and I haven't given up hope for better predictions.

Now, then, the TTAPS report has not discussed, as it stands, dependence on latitude or longitude; has made an assumption, no calculations, about rainout; has put at once the smoke into a layer where it would do most damage and where it could not appear earlier than in about 2 weeks; put it up there and do not—did not allow the winds which we know exist to move that smoke. They did not take into account vertical mixing which, due to the great temperature differences between ocean and land, were bound to occur, violent storms near the shorelines, which would probably cause vertical mixing, bring down the smoke into the region of the moisture and cause a fallout of that smoke by the vast amount of water.

I think I have explained why I would have never signed a paper of that kind. Now, then, additional papers have been published which took into account existence of the oceans, but made the instantaneous distribution of the smoke, the immobility of the smoke, still as assumptions. Making these essential and clearly false assumptions, you then got the same results.

I think that I would not sign such a paper, in fact, ever, because I'm not a meteorologist, neither is any one of your three present witnesses.

Mr. SCHEUER. Dr. Teller——

Dr. TELLER. But I have supported, served on committees, urged, argued and screamed for more research in that area. And as to your last question, are there still other disastrous effects——

Mr. SCHEUER. And what——

Dr. TELLER [continuing]. My answer is yes. My further answer is that none of us has imagination enough to know what they will be, but of one I know, and that, to me, is the most important: the psychological consequences of a war. Another—a third great war will destroy the traditions of Western Civilization and that, to me, is as dear as life itself.

And I will say to you, the effects are there. The effects that are calculable ought to be calculated. On that, we agree. Whether a tactic of frightening people by deemphasizing uncertainties and making statements that: "I have robust conclusions which predict with certainty the temperature drops", I do not believe that statements of that kind are in the spirit of science or in the service of public interest.

Mr. SCHEUER. Is there any way that you would suggest any changes in our national research design on a nuclear winter or any additions that would identify further areas of risk?

Dr. TELLER. It has——

Mr. SCHEUER. How would you perfect the national research design involving a whole multitude of agencies like the Department of Energy, NOAA, the U.S. Navy, the Defense Nuclear Agency, NASA, the National Science Foundation, the Federal Emergency Management Agency. These are just a few.

Dr. TELLER. I am not cutting into the subject of my honored colleague, Dr. Hecht, who will talk after me. I suggest that improved computers should be made available as soon as possible. I suggest that with the help of the shuttle, we should increase weather observations, make the whole of meteorology as much of a science and as little of an art as ever possible.

I would further suggest that discussions on all aspects of war should be made public; that the policy of secrecy should be drastically reduced and here I want to take the opportunity to make a recommendation, more important than any that has been talked about here yet.

Newspapers have appeared—newspaper reports have appeared about 5 years ago about a disastrous incident, strongly indicating that the Soviets are experimenting in violation of a recent treaty with a most dangerous disease, pulmonary anthrax. The Soviets admitted that thousands of people died of anthrax. When we asked to have autopsies to see whether it's pulmonary or intestinal anthrax—a very important point because one of them can be used as a weapon, the other cannot—the Soviets refused permission and I don't know of any other explanation except they're covering up an activity which is in violation of a treaty, fully as important, the ruling out of biological warfare.

Mr. **Scheuer**. Thank you very much, Dr. Teller.

Congressman Tim Valentine.

Mr. **Valentine**. Mr. Chairman, I don't have any questions. I would just like to express my appreciation to these gentlemen. They're all busy and have a lot of other things I'm sure they would prefer to do and I want to express my pleasure—if that's an appropriate word—for being a witness at this historic debate between these two national treasures on this question. I want to just say thank you.

Mr. **Scheuer**. Thank you.

Congressperson Claudine Schneider——

Mrs. **Schneider**. Thank you.

Mr. **Scheuer** [continuing]. Of Rhode Island.

Mrs. **Schneider**. I'd like to followup on your question, Mr. Chairman, in reference to the Federal research study program that is being conducted and I'd like to address the same question to Dr. Sagan and Dr. Gould.

Dr. Sagan, in your testimony, or your comments after your testimony, you had mentioned that there was a funding gap in that there was inadequate funding to study the biological impact. I wonder if you could please give us some of the key biological uncertainties or research questions that you believe ought to be investigated in the Federal research plan.

Dr. **Sagan**. Thank you, Congressperson Schneider.

Mrs. **Schneider**. Congresswoman is just fine. [Laughter.]

Dr. **Sagan**. But then, if it's Congressperson, it has to be applied symmetrically to Representative Scheuer as well. He can't be a Congressman if you're a Congressperson. [Laughter.]

Congresswoman Schneider, there is a, as you've heard, a wide spectrum of opinion on the consequences of nuclear war and I tried to stress earlier that even a small temperature decline might have very serious consequences. At the—at the very severe end of this discussion—in the range of what the TTAPS group and many others considered to be the most plausible consequences—very severe, more than a 10-degree temperature drop, for months, possibly for years, not restricted to northern midlatitudes, but worldwide. In a way, in that case, the biological problem is easier.

To quote Paul Ehrlich, he says that, "It's like asking a physician what would happen if you put a double-barreled shotgun in your mouth and pulled both triggers." The—the details of death might differ from physician to physician, but that it would be bad is quite clear.

On the other hand, if we go to small nuclear winter possibilities, a few degrees temperature drop, then the problem is more difficult. So consider the wide range of possible nuclear winter effects; include the severe end; include the modest end and try to understand what the biological consequences for all of those might be.

Such research can range from studies of individual organisms under stressed conditions—turn off the lights, freeze the organizm, or at least cool it, provide the toxic gases, the radioactive fallout, the possible increased ultraviolet dose after the soot and dust have fallen out and see what the consequences would be—to systematically studying closed ecosystems, microcosms.

Imagine a large terrarium, room size, at various latitudes corresponding to the kinds of plants and animals that exist in those various places and stress that closed ecosystem and see what the consequences are.

Mrs. SCHNEIDER. Well, Dr. Gould was making references earlier to the impact on phytoplankton and there we can look into the marine ecosystems, but do you feel that their—that the research plan, as it is currently designed, will adequately address the kinds of biological impacts on these ecosystems?

Dr. SAGAN. No, it will not address it at all because that either was not in the purview of the plan or was decided by the planning committee not to be an appropriate subject.

Mrs. SCHNEIDER. But you're saying that this is obvious—from your point of view, this is obviously critical that it be included——

Dr. SAGAN. This is obviously——

Mrs. SCHNEIDER [continuing]. Because it helps us to translate from the climatic and atmospheric to the ecosystem and then to the—the personal and individual impact——

Dr. SAGAN. Exactly.

Mrs. SCHNEIDER [continuing]. On homo sapiens.

Dr. SAGAN. So if you want to imagine three blocks of study, which are connected in just the way you said, but nevertheless, in my view should proceed in parallel, not in series, the first block is studying the atmospheric and climatic effects; the second block is, for the range of possible answers in the first block, what are the biological implications; and then the third block is, what are the implications for policy, doctrine, nuclear strategy, force levels of the possible biological consequences.

And the idea of doing this in series—first the one, then the next, then the next—means that you will not start seriously addressing the policy issues for years, possibly decades. In my view, this is a much too serious question to hold off until all the information is in and, as I said before, all the information will never be in, although it's very clear that we can significantly narrow the range of uncertainty in the results.

Mrs. SCHNEIDER. Dr. Gould, do you share this approach that has been recommended, that the three planes of investigation be conducted simultaneously?

Dr. GOULD. If they're not done simultaneously, we'll never get to what interests me most. They are such complex problems. I think the major point to be made about biological consequences is there are no systems more complex on this earth than biological systems. The more components you add, the greater the complexities mount.

I tried to make a distinction in my own remarks between the more uncertain but perhaps more frightening long-term potential consequences and the more immediate increments to human suffering. I think in terms of studying long-term consequences, there are three basic ways to go about it, all of which were, in fact, mentioned by Carl Sagan.

One can—the first two approaches are more directly and classically experimental. That is, you can study, first, the ecological tolerances and the responses; two, the presumed climatic and other effects of nuclear winter of individual organisms and species, but that doesn't answer the whole question because it's impacts upon ecosystems that counts, so there's then the second level which requires studying the coevolution and the coadaptation of creatures living in natural ecosystems, which is more difficult. It can still be done.

The nonexperimental or historical comparative approach is to study those historical events which may have been triggered in a similar manner—and we've gotten somewhere in that it's long been known, for example, that 1816 was an odd year. The famous year without a summer in both America and Europe, but I think it's only through the work of Henry Stommel and others now that we've, I think, firmly linked that very minor decrease in temperature with enormous consequences—Niagara Falls froze, but so did some very important sources of ponds for life that fed people, so there were direct important consequences there. But we can now trace this to the eruption of the volcano Tambora, which is a very minor event compared to what a nuclear winter might unleash.

And then there are the historical events of greater magnitude, the mass extinctions. We've made enormous progress. The Alvarez hypothesis of the cretaceous impact—I don't think we can assert for sure that his favorite killing scenario, which is so like nuclear winter, must be the cause of the extinction, but I think there is now very firm evidence that there was an impact—good, hard evidence, and finally, after a century and a half of paleontologists studying this issue, we're getting somewhere.

So that's how you study long-term consequences, but then there's the more immediate issue on which we have substantial agreement, namely the increment of human suffering, in which much can be done, particularly studying the impact of radiation and its various effects on human bodies and others; studying just how it is that agricultural systems will respond to very small changes in temperature; perhaps working to improve and otherwise alter agricultural stocks so that their sometimes frightening constitution as genetic monocultures growing at the edges of the ecological tolerance might be altered. So much can be done and should be.

Mrs. SCHNEIDER. Let me begin by saying that, of course, I think we all understand that Members of Congress like to begin and end their policy decision efforts from definitive points of reference. We like to have a yes or a no. Unfortunately, the nature of this job forces you to either be for or against, pro or anti or whatever.

You gentlemen, as scientists, of course, have the opportunity to—or freedom of decisionmaking that is based on scientific experiment and, granted, after a certain number of experiments are concluded, you then come up with your proposal or your theory, and most of the time those theories are not 100 percent yes or no or black or white or pro or anti or whatever.

However, is there a generally agreed upon threshold in the science community, a threshold that is believed to trigger a nuclear winter? What are some of the parameters of the equation for what we believe will trigger a nuclear winter?

Dr. Sagan.

Dr. SAGAN. Well, the—the idea of a threshold is one that was introduced in the TTAPS paper and that I've discussed in my Foreign Affairs article in the arena of implications for policy and doctrine. I stressed there and elsewhere the enormous uncertainty in where that threshold lies and I think that uncertainty is itself a good thing and has itself strategic significance.

Nevertheless, if you look at the TTAPS calculations, you will find that the destruction of something like 100 downtowns at northern midlatitudes seems to be sufficient to trigger a very major nuclear winter, and it's possible that the destruction of a—the burning of a smaller number of downtowns would affect—it seems likely for those parameter choices—would lead to very serious consequences. And that in turn implies that with the ability to destroy more than, say, 100 downtowns—I'm picking a very rough number—there is the ability to destroy more than the global civilization—something conventionally called, and I know Dr. Teller doesn't like the word,"overkill."

And the question of where this threshold lies depends on many imprecisely known parameters, the most serious of which is the question of targeting, because humans have done what in retrospect may look like a foolish thing: They've gathered themselves together in and concentrated their populations in a few locales where there is an enormous concentration as well of combustible materials, and therefore, the targeting of cities or strategic targets in which the cities are accidental and ancillary targets, leads to this possibility—that merely a small number of cities burned may trigger nuclear winter.

Dr. TELLER. May I give a direct answer to Congresswoman Schneider?

Mrs. SCHNEIDER. Yes, Dr. Teller.

Dr. TELLER. You have seen the diagram—if possible, I would like to have it back on the screen, but it's not absolutely necessary.

Mrs. SCHNEIDER. Well, that's all right, I recall the——

Dr. TELLER. You can see——

Mrs. SCHNEIDER. Yes.

Dr. TELLER [continuing]. That if you reduce the smoke by a factor of two, then instead of a temperature decrease, which is sizable, you get temperature changes which are in some cases negative; in some cases, positive. If there is an indication that is not a robust fact, it is not science; it is a little deviation from ignorance. If there is an indication of a threshold——

Mrs. SCHNEIDER. OK.

Dr. TELLER [continuing]. Then the calculations so far—and that may change—seem to show that about one-half of the smoke assumed in the paper of Turco and others, about one-half the smoke is already below the threshold. Now, if somebody is dedicated to exaggeration, we can't stop him.

Mrs. SCHNEIDER. Well, I wonder——

Dr. TELLER. If somebody wants to have certainty where there is none, we can't stop such assertions.

Mrs. SCHNEIDER. Well, as I had——

Dr. TELLER. But what little——

Mrs. SCHNEIDER [continuing]. Stated earlier, Dr. Teller, we do—we do understand that scientists do have to work with various assertions and that conclusions are not quite as definitive as many of us would like. We do understand that.

Dr. **Teller**. That is what I am agreeing on, and I want to——

Mrs. **Schneider**. But for policy decisions—that is useful for us in policy decisions to have parameters of understanding of, you know, what that impact would be.

Dr. **Teller**. We share an understanding that an increase in funding for climate changes is important. We had a very weak indication——

Mrs. **Schneider**. OK.

Dr. **Teller** [continuing]. That the threshold for nuclear winter, if there is such a threshold, may be not at 225 million tons of smoke, which was assumed by Turco and others, but at about half that much, approximately 100 million tons of smoke, and that is as much of a quantitative answer to your question as is now available from actual calculations, rather than from guesses and speculations.

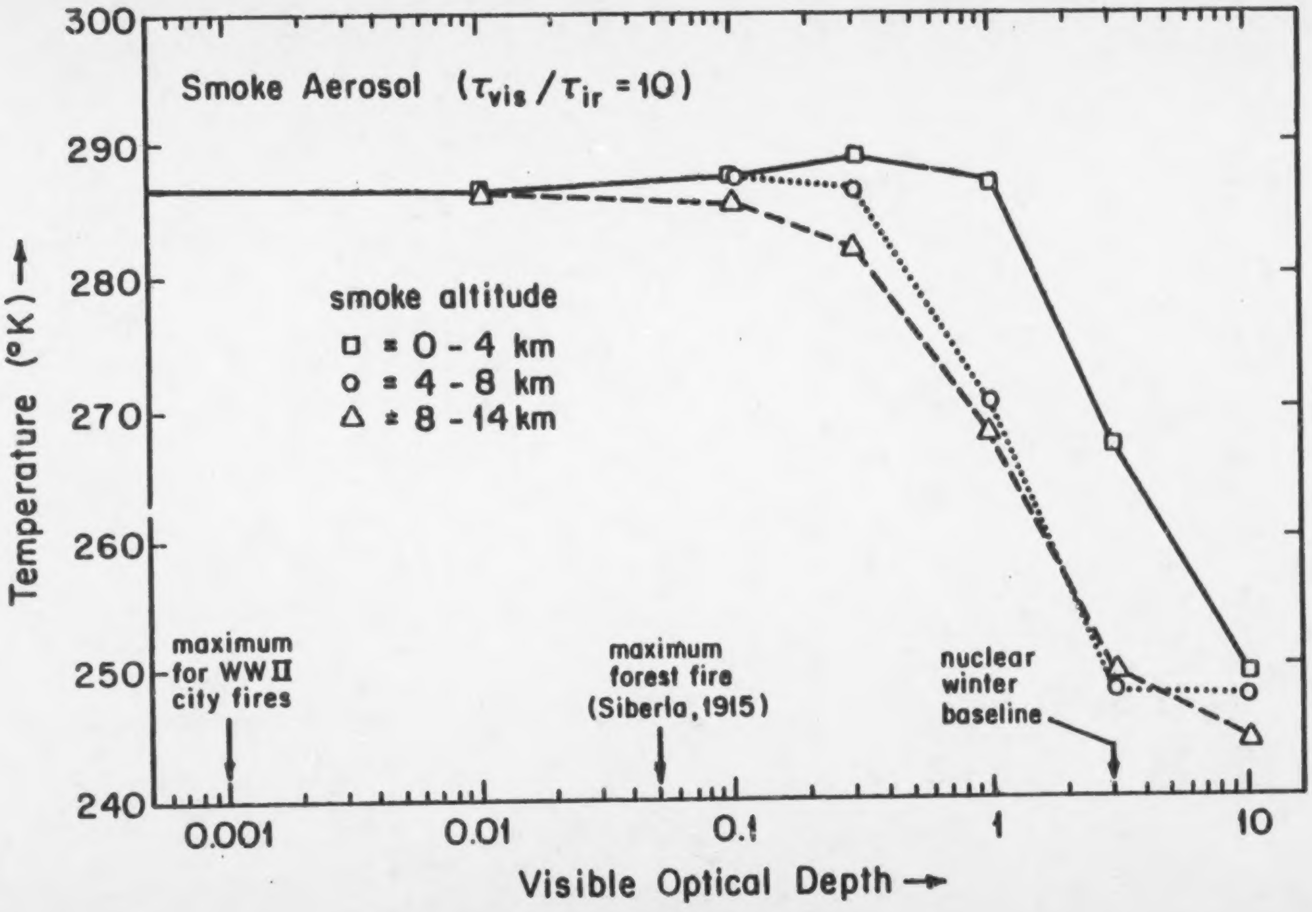
Mrs. **Schneider**. I thank you. I was given the word from the chairman that I have to move along.

Dr. Sagan, perhaps you could supply us with your response in written form because we are—do you want to do it now? All right. So the chairman says go, so——

Dr. **Sagan**. On the question of threshold, what I'm saying now is not fact, as far as I understand, but from what Dr. Teller was saying, but maybe as far as he understands, it is. This is a calculation of temperature as a function of optical depth, and for optical depth, just think of the amount of smoke up there.

The temperature here, with very little smoke up there, is something like 286 degrees—that's 13 degrees Centigrade—that's an average temperature at northern mid latitudes. As you get more smoke, depending on whether the soot is close to the ground or high up, the temperature averaged over the Northern Hemisphere changes as you see. So this is the idea of a threshold.

[Material referred to follows:]


Smoke Aerosol ($\tau_{vis} / \tau_{ir} = 10$)
smoke altitude
□ = 0 - 4 km
○ = 4 - 8 km
△ = 8 - 14 km
Temperature (°K) →
300
290
280
270
260
250
240
0.001
0.01
0.1
1
10
Visible Optical Depth →
maximum for WW II city fires
maximum forest fire (Siberia, 1915)
nuclear winter baseline

Mr. **Scheuer**. Excuse me, when you said the Northern Hemisphere, that would include the United States, Canada, also the food-growing areas of the Soviet Union, their wheat-growing areas?

Dr. **Sagan**. That's right.

And as you see, you go along increasing smoke into the atmosphere for quite a while. Very little happens, and then you get around this place and suddenly the temperatures drop fairly precipitously. That's the idea of a threshold. It doesn't mean a right-angle turn, but it's a fairly steep change and——

Mr. **Scheuer**. That would be a sort of a critical mass that you're hitting there.

Dr. **Sagan**. Critical amounts of fine particles, especially absorbing soot in the atmosphere and the—the number around here is something like 100 million tons of soot, so that's the general idea of—of a threshold, but how much you have to burn to put that amount of soot up into the atmosphere is still a matter of some discussion.

Mrs. **Schneider**. One very quick question—hopefully with a brief answer—I was just rather curious. During the 1950's, the United States and the Soviet Union did a significant amount of large nuclear testing and I was just wondering, is there significant data that has been accumulated that has studied the effect on the world's climate as a result of that testing?

Dr. **Sagan**. Because, fortunately, those nuclear explosions were not done over cities, but over deserts, tundra, coral atolls, and the like, there was very little soot produced in those—in those explosions, and we calculate that there should not have been any measurable temperature declines in the testing period that ended with the Limited Test Ban Treaty of 1963 and, as far as we can tell from the historical climatic records, there is no such change.

Likewise, burning of large fires in the past, we calculate should not have produced a—a major change and the burning of the cities in World War II should not have because they were spread out over a period of a few years, rather than all the cities simultaneously being burned in a nuclear war.

Mrs. **Schneider**. Well, I thank you very much for your insightful testimony on the part of all three of you. I think the chairman should be commended for bringing together such terrific expert witnesses and for highlighting the information that has been generated here today.

Thank you, Mr. Chairman.

Mr. **Scheuer**. Thank you.

Can I ask you, with your extensive contacts in the international scientific community, have the—has the Russian scientific community and perhaps, to your knowledge, the top Russian military authorities—their Joint Chiefs of Staff—been appraised of this whole question and have they—are they in the process of factoring it into their geopolitical policymaking decisions?

Dr. **Sagan**. In a——

Mr. **Scheuer**. Excuse me. Have our institutional decisionmaking apparatus involving the White House, the State Department, Secretary Weinberger, the Joint Chiefs of Staff, and the other defense planning agencies—have they factored all of the likelihoods of this kind of a disaster—of various possible degrees of likelihood—have they factored it into their thinking?

Dr. **SAGAN**. In January of this year, Dr. Gould and I were at a meeting held by the Pontifical Academy of Science in the Vatican City on nuclear winter. Incidentally, we had the chance to brief the Pope on the subject. The leader of the Soviet delegation was Y.P. Velikhov, the vice president of the Soviet Academy of Sciences. Dr. Velikhov told me that he had personally given what he described as extensive briefings on nuclear winter to Defense Minister Ustinov and Foreign Minister Gromyko.

Mr. **SCHEUER**. Does Velikhov think that this is a plausible threat.

Dr. **SAGAN**. Velikhov has publicly stated, for example, in hearings that Senators Kennedy and Hatfield called last December, that he considers nuclear winter to be serious, worthy of more study, but to have very serious policy implications. On the U.S. side, I know from personal experience that at least the uniformed part of the military establishment of the United States has been very open to the nuclear winter discussion, as has the intelligence community, and I've given briefings to the Arms Control and Disarmament Agency on it. I do not know from firsthand experience whether the President or the Secretary of State or the Secretary of Defense have been briefed on this subject. I certainly hope so.

I might mention, Mr. Chairman—I don't know if in the interests of time you want to follow it up—that there is in the hearing room, Dr. Vladimir Aleksandrov of the Computing Centre of the Soviet Academy of Sciences. I discovered yesterday that he was going to be here and he might have an opinion on Soviet views of the subject.

Mr. **SCHEUER**. He's going to be introduced at the time of the next panel.

Dr. **SAGAN**. Oh, great.

Mr. **SCHEUER**. We will ask him to say a word.

Dr. **SAGAN**. Good.

Dr. **SCHEUER**. Dr. Teller.

Dr. **TELLER**. We had several meetings, international meetings, with the Soviets present.

Mr. **SCHEUER**. Military or scientific?

Dr. **TELLER**. Scientific—for the purpose of what can be done on our part to avoid nuclear war. The question of nuclear winter was discussed last summer in August and I was present and participated and also this summer and I was not present. Several of our people from Livermore who have long experience presented their results. One of the most important results was the chart that I showed you that was shown in that international meeting. Velikhov and I had detailed discussions as to what is to be done, that we should discuss, that we should clarify issues. Velikhov, in spite of several chances to participate in discussions with me, did not take advantage, even though a formal document has been signed. Instead, without discussion, the vice president of the academy has given public testimony directed at the American people.

Now, I can answer another question. The President's Science Adviser is fully and in detail informed of the nuclear winter issue and has taken action on it. There is no question from Richard Wagner's testimony that our military know about it, and look at it with quite a bit of doubt, but even greater seriousness. That is the impact of Richard Wagner's testimony. That is its real meaning. That our press has taken it seriously; that our people get excited about it as they did about fallout and about the ozone layer, which are no longer considered as seriously because more research was done on it, that American people are being told that these dangers exist is quite clear. To what extent and in what way the Russian people know about it, I do not know, and fear may not be the right counselor. Unilateral fear may be a less reliable counselor.

Mr. **Scheuer**. This is the——

Dr. **Teller**. Caution, sir——

Mr. **Scheuer**. This is the peace-at-any-price syndrome that you're referring to, I suppose.

Dr. **Teller**. Caution most certainly, and determined efforts for defense, for destroying nuclear weapons in action before they can do damage—on which we are working with all possible means—those of us who are interested in the defense of the country. These are clear points.

Mr. **Scheuer**. Thank you very much, Dr. Sagan—Dr. Teller. Did you want to add——

Dr. **Sagan**. Yes, sir. Dr. Teller has raised the specter of a fear gap between the Soviet Union and the United States. The United States, he's worried, might have more fear about nuclear war than the Soviet Union, which might redound to our disadvantage. Let me assure Dr. Teller that, from publications in Pravda and programs on Soviet television, that there has been widespread coverage in the Soviet Union of the nuclear winter issue, dating back to last October and continuing—I received a clipping just a few weeks ago about something published a few weeks ago—so there is continuing public discussion in the Soviet Union about nuclear winter and maybe in the next panel, your witness will be able to say more about that.

Mr. **Scheuer**. Thank you very much. This has been a—an enormously interesting and stimulating panel. We've gone way over our time, as you can see, only because you have gripped us with your fascinating and challenging testimony. Thank you so much.

We'll now go to the second panel and we'll hear Dr. Alan Hecht, Director of the National Climate Program Office at the National Oceanic and Atmospheric Administration. Dr. Hecht was formerly with the National Science Foundation and is currently coordinating the production and implementation of the Federal research plan, if you can dignify what goes on out there in the Federal Government among these six or eight agencies as a plan.

Dr. Hecht, we're very happy to have you. We know that you have a Russian scientist as our guest at these hearings. If he would wish to join you and make a brief statement, we'd be very happy to have him do so, entirely at his discretion and yours.

STATEMENT OF DR. ALAN HECHT, DIRECTOR, NATIONAL CLIMATE PROGRAM OFFICE, NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION; ACCOMPANIED BY VLADIMIR V. ALEKSANDROV, PH.D. HEAD, CLIMATE MODELING SECTION, COMPUTING CENTER OF THE U.S.S.R., ACADEMY OF SCIENCES, MOSCOW

Dr. HECHT. One of the reasons I asked Dr. Aleksandrov to join me is I know that you often ask witnesses to talk among themselves, and since I was the only one in the panel, I wanted to avoid the circumstance of having to talk to myself. [Laughter.]

So it's fortuitous that Dr. Aleksandrov is actually here with us.

Before I introduce him, though, I would like to make a few remarks. I think the conclusion from the previous panel, from people who have widely different views of the subject, is that a certain amount of research is needed—a research program is needed to look at the uncertainties of the hypothesis of nuclear winter. So, in effect, I can rest my case, although I'm not really here to argue a research program at this point, but to give you a progress report on the preparation of just such a program.

As you might imagine, I'm in a somewhat uncomfortable position. This plan is being drafted—and I will describe a little bit about its progress, but it has been requested by OSTP and it requires a review by the agencies involved, all of which have yet to occur. So there's somewhat a tentativeness of what I will say with respect to the plan only in deference to the people who really have to review it and agree with the overall structure of it.

As Dr. Sagan has said, he, along with many others, was a reviewer. He raised an issue about the extent to which the plan covers a certain aspect of the assessment, the biological consequences, and I think that is very good because part of the process of developing the plan is a peer review, and in the course of that peer review, new ideas may be introduced which will change the ultimate scope of the plan.

Now, let me—in a few minutes, and I know you're running late, Mr. Chairman—just make one statement about the process of the development of this plan and then make some general observations about the science involved.

The origin of the attempt to develop a plan goes back to February of this year when NOAA Administrator John Byrne and I visited with Dr. Keyworth to ask for guidance on certain aspects of climatic research as it pertained to the nuclear winter. And as Dr. Teller has suggested, Dr. Keyworth was very well informed of the subject and gave us a tutorial, the end of which was the request and a need for him to see many aspects of the research developed, and he asked that such a plan be developed.

After that meeting, an interagency committee, under Dr. John Byrne of NOAA, was organized to actually discuss what a plan really is. Time and resources do not permit—or did not permit a major assessment of the problem which is actually being done by the National Academy of Sciences. Rather, what was proposed and what was directed at me was a structure for a design of a research program, and with certain bounds, I proceeded from there to organize such a plan.

A drafting committee was organized and the drafting committee represented both university and agency people who had been involved in the issue from the time it was first published. I like to describe it as 30 percent of the TTAPS group, 50 percent of the Crutzen/Birks group, 30 percent of the—33 percent of the Schneider, Covey, Thompson group and so on down the line, mainly to illustrate that many of the people whose names have been associated with publications of this subject were included in the drafting committee. Those who were not or could not make the meeting were assigned to the review committee. My testimony includes the names of those people who contributed to the drafting. An equal number of people have contributed to the review, which is just about now complete.

That committee met on May 7 and 8 and it's only a few months now since then and we are almost to the point of a final plan. All the reviews are in. All the recommendations have been modified or addressed, including the issue of the biological consequences and as you understand, I will skip over much of the details, but only say that next week the plan will be reviewed by an interagency committee and I would predict that within a month's time, it should be available to the general public.

Now, let me make some scientific observations and I'll preface it by saying that nuclear—to really do this problem right, it's become apparent, not only from the drafters of the plan, but from, I think, everyone who's looked at it and tried to take it apart—that it is an extremely complex problem. It is actually several problems embedded in even bigger problems.

The drafting committee had no trouble identifying uncertainties and generally where there were big holes in understanding. But it became much more difficult, even initially, to try and get some good information or research data on it. For example, just in the case of fires, as we're learning, based on a meeting that is now in progress, that while we could ask certain questions: What are the size of particles that will be lofted in the atmosphere; how high up will it go; how long will it stay and so on and so forth, it was very difficult from the literature and from common experience to answer the questions.

The experiments that were done were not quite in the right size range; they were not quite of the right magnitude; they were not quite of the right materials and so on. So it became apparent that we were in many ways breaking new ground in areas that turned out to be very fundamental subjects.

In the area of modeling, for example, climate modeling, the nuclear winter problem is actually embedded in a broader problem of understanding mesoscale circulation. Understanding the source imput of nuclear debris is embedded in a far broader problem of fire phenomonology. I underscore this because it says in the final analysis, there are no quick experiments; there are no simple model runs; there are no simple answers to the very complex problem. It's going to take a fair amount of concentrated work and effort—often in some very fundamental subjects—before the uncertainties can be reduced.

Now, during the course of preparing the plan, and I think from looking at the published literature on the subject, it becomes apparent that it is an interdisciplinary and interagency problem. The TTAPS paper includes two scientists from NASA, or rather, three. Crutzen and Birks includes university scientists. The modeling studies include NCAR scientists, the National Science Foundation. The fire research people include the National Bureau of Standards and many private groups. University scientists at all levels have been involved and it becomes clear that to underscore and really do something with the problem, an international—an interagency program is needed.

If you study fire in the field, you need to measure all the parameters. You need aircraft; you need ground equipment; you need to know meteorology, and from that comes a common theme that runs through the plan, which is the need to bring experimenters and model developers and researchers all together and focus their attention. It's not to say that there isn't room for the free writing of proposals here. It's not that kind of directed effort, but there's clearly a need for an integration of a lot of disciplines to address the problem.

When the problem is dissected, several things become apparent. First, the laboratory and laboratory research can contribute an enormous amount of information to the study of the problem. At first, that may seem strange. Large fires, nuclear explosions—enormous in scale—but yet when you start looking at the assumptions and you start arguing over the details, many of them can be approached in a laboratory environment and that is one of the things to be underscored; that there is a way of approaching the problem.

A suite of experiments is actually needed and is actually proposed by the drafters of the document, from the bench scale experiment to the room-size experiment, to the house-size experiment. A whole suite of experiments are designed to better understand the source material; how much, how high, how long will it stay in the atmosphere? How much of the smoke is rich in carbon?

All the modeling results that have been published begin with a large amount of smoke and dust in the atmosphere. Given various assumptions, they follow the course of the modeling experiments. They generally come to reasonably same conclusions if you understand the assumptions.

But the crucial question—or a crucial question—is how does that smoke get there in the first place? How high will it really go? What will happen on the scale of clouds and mesoscale circulation? Will it all rain out? And these are questions that are very, very difficult to answer.

Concurrent with the experiments, both in the laboratory and in the field, we can improve our modeling capability. We can make the modeling experiments that have been done more realistic. Instead of keeping them as perpetual sunlight, you can make them day-and-night experiments.

But—and I underscore again why we present a program that ranges over the next 5 years. There's a limit, a reasonable limit that can be expected for vast improvements in the general field of atmospheric science. It needs the thrust, I think, as everybody agrees, but it isn't going to be solved in a 5-year period.

Hard choices have to be made and the plan gives some emphasis to the source material, the subsequent movement in the atmosphere and then the air effects. The purpose of the plan, the structure of the plan, is to look at many of the issues raised by TTAPS and others, including the toxicology. We can't do everything, but I think our first approach is to find out which of these problems are really serious; which are going to require more effort; which are going to require another plan, and hopefully another coordinator. To put a plan together for the biological consequences is going to be a very complicated job.

Last, I think what emerges from all our efforts is the need to do this internationally. There's only finite resources available to us and to everyone else; there are only a finite available number of fires that we can study. We're breaking new ground. Some of it is research so basic that it would be hard to imagine that it would be useful for a problem of this type. Our resources and the leverage on the problem can be vastly increased if we can do it collaboratively and in a proper international forum.

And many of the areas are safe. We don't have to exchange with my colleague here our nuclear war scenarios, but we can certainly talk about theoretical work on fires, fire experiments, modeling, and the like.

Mr. SCHEUER. When you say it would be desirable to do the research properly—in the proper international—cooperatively in the proper international forums, can you give us a little more in the way of specifics on that——

Dr. HECHT. Well, I think right now——

Mr. SCHEUER [continuing]. Cooperatively with whom and what forums, to what end?

Dr. HECHT. Right now, there's an international group under ICSU, SCOPE, Scientific——

Mr. SCHEUER. Want to spell out ICSU for the record.

Dr. HECHT. I-C-S-U, [International Council of Scientific Unions,] and more specifically, SCOPE, [S-C-O-P-E]. It's an international group that is looking at all aspects of the nuclear winter scenarios and its effects. Nongovernmental for one thing.

That is an example of a kind of forum where a lot of research can be done. We have in the United States several bilaterals with our colleagues in the Soviet Union and I'll describe that in a minute. That's another possible forum.

The point, not to argue detail here, is simply to say that it has been individual scientists in the university community, not necessarily Government scientists, who have first addressed this issue and there's an international community of scientists out there that want to work on the issue.

Mr. SCHEUER. Does that include Russian scientists?

Dr. HECHT. Yes, it does.

Our emphasis is on accumulation of new data, data management of these data and the availability of the data, internationally as well, so that the proper climate scenarios can be developed for doing all the assessments and for doing all the policy implications.

I conclude by saying that since I've worked on this since February, I've become an expert on fires and nuclear war scenarios and a lot of other things, and I am in the most perfect position relative to the previous panel, which is right in the middle. I don't have to agree with anybody, but I recently finished a book by Freeman

Dyson, which is "Weapons and Hope," his new book, and I found a quote in there which I think is appropriate to end my discussion. He made the quote in reference to the original Ambio study. I am taking the liberty of extending it to everything done since then.

The quote from Freeman Dyson is parenthetically, my extension to everything else since then.

> The Ambio study is important, even if one does not believe—believe its numerical conclusions. All of its assumptions and all of its detailed results are open to challenge. Alternative and equally plausible assumptions give widely different results. The study does not, as some of its authors claim, make our knowledge of nuclear war more precise. The study is important for the opposite reason. It has shown us that our ignorance of the effects of nuclear war is even greater than we had realized.

And I think that's ample reason for the research plan that has been initiated and I hope that I can—when that plan is published—share it with you, as I am sure you will be very anxious to see it.

Now, let me take one more moment. In the last 10 years, I have been involved in implementing the United States/Soviet bilateral in environmental protection and under that bilateral, I've been cochairman of the Working Group on Climate, so I have worked extensively with my colleagues in the Soviet Union, and in the course of that work, we have done a great deal of climate modeling work together.

With me today—just by chance, mind you—is Vladimir Aleksandrov, from the Computing Centre of the Academy of Science, a very frequent visitor to the United States. He's here so much that I think we should give him honorary citizenship. I'm sure this is an important lesson in civics for him to see how things work here. I'm looking forward to an equal chance to learn civics in the Soviet Union—but we've also been together on a number of other meetings on this subject, and if you like, Mr. Chairman, I've always known—I've known Aleksandrov for a number of years, and he never passes up a chance to at least say something.

[Laughter.]

But if you'd like him to make a comment about the work in the Soviet Union, I'm sure he'd be delighted and after that, I again express my appreciation to you for the opportunity of putting me in this uncomfortable position and I'd be glad to try and answer any of your questions.

[The prepared statement of Dr. Hecht follows:]

STATEMENT BY DR. ALAN HECHT, DIRECTOR, NATIONAL CLIMATE PROGRAM OFFICE

Mr. Chairman, thank you for the invitation to testify on the organization of a research plan to assess the environmental consequences of nuclear war. A research plan is being prepared at the request of the Office of Science, Technology and Policy. My discussion today is a progress report on the preparation of this plan. The final plan will be reviewed by the agencies involved before it is submitted.

The hypothesis underlying a "nuclear winter" is that dust raised by nuclear explosions and smoke produced by thousands of fires caused by a moderate or large scale nuclear exchange would spread over much of the globe and block sunlight to an extent sufficient to cause surface land temperatures to drop below freezing for up to several months. The potential disastrous global consequences from such a "nuclear winter" have important implications for nuclear policy. Preliminary scientific estimates of the effects are, however, based on many assumptions and uncertainties. These include nuclear war scenario, estimates of how much smoke is produced during fires, how much dust is raised by explosions, how high smoke and dust are injected into the atmosphere, how long and how much of the material is retrained in the atmosphere, how the smoke and dust interact with and are distributed in the atmosphere, and how this material alters the radiation balance and general circulation of the atmosphere.

To respond to a request for a research plan which addresses these major uncertainties, an Interagency Drafting Committee was formed. The Drafting Committee included many government and university scientists who have been involved in this issue since it was first proposed. My testimony includes the name of members of this Committee. An equal number of other scientists have been asked to review the plan. The plan lays out in basic strategy for a research program.

The main recommendations of the Drafting Committee are that an interagency effort be organized (1) to design and implement a suite of carefully planned laboratory and field fire experiments and (2) to develop the predictive capability to narrow the fundamental uncertainties of source inputs to the atmosphere and subsequent radiative, cloud, and chemical interactions in the atmosphere.

Laboratory experiments can help in determining the amount of smoke formed in initial fires, the aerosol yield from mixed fuels, the chemical composition of the smoke (especially the fraction of graphitic carbon) particle sizes and optical properties of smoke, coagulation potential of mixed fuel sources, and dynamics of mixed fuel source-smoke interactions. A few of large scale fires are purposely set each year by forest managers, and these can provide one means of conducting field studies, but such studies must follow experimental work.

Besides experimental studies of individual fires, there are regional scale natural phenomena which have some characteristics of the aerosol input of a "nuclear winter". The two best known analogues are the burning of tropical forests in slash and burn farming, and dust storms. By measuring the amount of soot which is naturally injected in the atmosphere and the steady-state loading of the atmosphere in the tropics insight may be gained into the processes that remove soot from the atmosphere. Saharan dust storms are optically dense enough to cause surface temperatures to drop many degrees. Studies of these events may better reveal how the thermal structure of the atmosphere changes when aerosol clouds are present and how aerosols are transported and removed from the atmosphere.

Concurrent with the above efforts, the Interagency Drafting Committee recommends a well-organized effort to improve fire and atmospheric modeling from small to large scales, and including the important interactions among various scales. These models are crucial for decision making at all levels. A series of model improvements in physical representations and perameterizations in existing general circulation models is necessary to provide a more realistic assessment of climatic consequences. New observational data derived from fire experiments and natural phenomena would also be useful in validating the models.

Evaluating the first order climatic consequences of nuclear war is extremely complex and requires the expertise of many disciplines. A carefully planned coordinating reasearch effort is required to develop a more realistic picture of possible environmental consequences. Not all uncertainties can be eliminated but a better knowledge of the range of possibilities can be obtained. It should be emphasized that the nuclear winter problem is embedded in a more general problem of understanding mesoscale circulation and cloud dynamics. This is a major challenge in atmospheric science.

The combined efforts on theory, experiment, observation and modeling, linked together, can provide maximum scientific leverage to reduce major uncertainties in understanding atmospheric consequences of nuclear war.

The research plan emphasizes first order atmospheric effects. It provides for exploratory review of issues raised by scientists who have studied the problem. The goal of model and experiments in the program are to define a set of climatic scenarios against which biological and human assessments can be made. Concurrent development of unclassified nuclear exchange scenarios by DNA and DOE will be used for input to the modeling studies. Results of all studies will be unclassified and available to the scientific community through standard scientific journals and technical reports.

This concludes my prepared remarks. I appreciate the opportunity to discuss our progress in developing this program and I would be happy to answer any questions you might have.

DRAFTING COMMITTEE

A.D. Hecht, National Climate Program Office, Chairman.

Dr. Marvin C. Atkins, Deputy Director, Science and Technology, Defense Nuclear Agency.
Dr. Eugene W. Bierly, National Science Foundation.
Dr. David W. Bensen, FEMA.
Dr. John Birks, University of Colorado.
Dr. Joseph Bishop, FEMA.
Mr. Jack Campbell, Environmental Protection Agency.
Dr. Robert D. Cess, State University of New York.
Dr. Vernon Derr, Environmental Research Laboratory, NOAA.
Mr. Peter Lunn, Defense Nuclear Agency.
Dr. Michael MacCracken, Lawrence Livermore National Laborartory.
Mr. Harry R. Marshall, Jr., Prinicpal Deputy Assistant Secretary for OES Department of State.
Dr. Michael May, Lawrence Livermore National Laboratory.
Dr. Harold D. Orville, South Dakota School of Mines and Technology.
Dr. James Pollack, Ames Research Center, NASA.
Dr. Lawrence Radke, University of Washington.
Dr. Starley Thompson, National Center for Atmospheric Research.
Dr. Brian Toon, Ames Research Center, NASA.
Dr. Darold Ward, U.S. Forest Service.
Dr. Martin Yerg, National Climate Program Office.

Mr. SCHEUER. Well, thank you very much, Dr. Hecht, and welcome, Dr. Aleksandrov. We're delighted to have you here. We would like to hear from you. We do have a force of public opinion in this country, as well as congressional opinion, and these hearings are designed not only to educate the Congress, but to educate the American people, who make themselves felt in a whole variety of ways, one of which is to preserve some of us as incumbents—you've heard that word before this morning [laughter]——

And eliminate others of us, a little bit less painfully than the scenario that we heard. [Laughter.]

I'm not sure you have quite the same powerful public opinion as a fact of life that impinges upon decisionmaking in the Soviet Union, but that's neither here nor there. We are delighted to have you and we'd be happy to hear any words you might have to tell us, especially about the degree of interest in the subject of nuclear winter by the Soviet scientific establishment, as well as the Soviet military establishment; what is the degree of their interest; what kind of scientific work are they doing on the matter; what do you look forward to in terms of joint collaboration on joint scientific enterprises with the United States; and perhaps some kind of joint decisionmaking on ways that we can avoid nuclear holocaust and the resulting nuclear winter.

Dr. ALEKSANDROV. Thank you, Mr. Chairman. I am very glad to and I have a big honor to be present here and thank you for the possibility to give me a possibility to have a talk.

I would like to answer to your questions in a consecutive way. I don't belong to a newspaper, so probably I cannot answer on the question which I hear every night from the TV: Do you want to know what Soviet military are playing. So as for newspapers and magazines, I think we have pretty good coverage of this topic in the Soviet Union.

For example, we have the transmission of this Moscow link which was—which took place after the conference, The World After Nuclear War, 31st October, 1st November, and then we have pretty extensive number of articles in our newspapers. In Pravda, for example, the article written by the Deputy Director of the Computing Center of Academy of Sciences was published—was published, oh, about two months ago, more than in 100 newspapers all over the country. So this topic is pretty well publicized in the Soviet Union.

As for scientific side, I can say that we are talking about the pretty vast research in this field, including the numerical modeling of climate, the microphysics and the study of mass fires and many institutions of Academy of Sciences are involved in this business or plan to be involved, as, for example, the Computing Center of the Academy of Sciences' Institute of Atmospheric Physics, Institute of Chemical Physics, some institutions of hydromet service and so on.

As for me personally, and as for Computing Center, we continue our research in numerical modeling of the global consequences of nuclear winter and we just performed the calculation, in which we used a model which takes care about the global circulation of atmosphere, the behavior of upper layer of ocean, and in the same time, it takes care about the—about the transport of soot and dust all over the globe, which, in its own term, controls the sun—the sun is flux to the Earth's surface, to the climatic system.

And I had—I had an excellent possibility to show the results at the conference in Maryland—Nuclear Deterrence; New Risks and New Possibilities—to which I was invited—as invited speaker, which took place from 5 to 7th September at Maryland University and I had shown these results yesterday on this NBS conference dedicated to mass fires—to big fires, and at the same time, probably we'll take part also in program dedicated to fire research, so we are pretty busy in these—in the study of this topic.

I would like to thank very much Dr. Alan Hecht for the fruitful cooperation which we had in recent years between Soviet and American scientists in the field of climate modeling and after these exchange programs, I visited sometimes the United States for different terms and so I had a possibility to work in major American institutions on this topic, and we had a lot of American scientists in our institutes and in the last few years, we had probably at least 20 American scientists—maybe less, maybe 12, 15 American scientists in Computing Center—so we had a perfect possibility to—to talk with other—with each other about the topic—about this topic and just recently, in first 2 weeks of August, we had a group from Lawrence Livermore people in our institute so we have a 3-week, 3-day discussion about the climatic consequences of the nuclear war and I think that this cooperation is extremely fruitful and useful for mutual understanding of the possible consequences of the nuclear war.

Thank you.

Mr. SCHEUER. Thank you very much.

Congresswoman Schneider.

Mrs. SCHNEIDER. Dr. Hecht, I was wondering if you could just tell us to what degree you think that, despite the fact that the report is due out shortly—what did you say this week or this month?

Dr. HECHT. No, next month.

Mrs. SCHNEIDER. Next month. You heard the testimony having to do with the biological consequences and the need for inclusion in the overall study. Could I hear some comments from you on that, please?

Dr. HECHT. Raised by several reviewers as part of the overall review, I think in the plan I'll be generous to myself and say we didn't go far enough, but I think it's for the agencies involved to make the final decision, so those reviews——

Mrs. SCHNEIDER. Well——

Dr. HECHT [continuing]. Plus the plan will be presented back to the agencies and we'll make whatever changes they—they feel are necessary.

Mrs. SCHNEIDER. And when will this plan be available for public consumption?

Dr. HECHT. Well, I've tried very hard to keep a—the schedule that we agreed earlier. Next week the Interagency Committee will review the plan and, given the final changes, it will be presented to OSTP who requested it originally. That takes us into October and at that point, it will be available for the community as a whole—public to look at it.

Mrs. SCHNEIDER. What are the—you had mentioned the need for international cooperation which I, too, think sounds like a good idea. But you were primarily, I believe, referencing the need to share the research end of it. To what degree will this study also be shared with our international colleagues?

Dr. HECHT. This—you're asking about policy?

Mrs. SCHNEIDER. Yes.

Dr. HECHT. This study is in the context of providing the best scientific information that we can to policy people. It doesn't—we're not dealing in here—and it's outside my area, certainly, for policy considerations, but the—it is tied in a way that it's—it will get the best information with all the uncertainties that will remain, as you underscored, to those who have to make policy decisions. So it does—it stops short of dealing with policy issues.

Mrs. SCHNEIDER. But right now, you don't have any kind of mechanism in place whereby you will share the information with other countries, or do you have a mechanism in place to do that sharing?

Dr. HECHT. Well, there are several mechanisms besides bilateral exchanges and besides ad hoc meetings such as the ones that have occurred in Sicily every year for the last 4 years and many other international opportunities and, as I described, this SCOPE Committee, I think there are many mechanisms for exchanging at least the scientific information, but I would not—I am not knowledgeable about all the other forums in which the policy considerations are also being discussed.

Mrs. SCHNEIDER. But perhaps you would be interested in setting up a task force among your interagency groups——

Dr. HECHT. No, the management of——

Mrs. SCHNEIDER [continuing]. To make recommendations for the distribution of this?

Dr. HECHT. The management of this plan is one that's crucial and it—not only to ensure the research, but also to ensure simply information flow. I won't reveal to you the name of an agency that I've received three phone calls from from three different people, all of whom were not quite certain what the other part of the agency was doing, and they were all—thanked me for telling them what was going on. But I think there's a need for a flow of information and that will be provided for, I think, once the agencies involved approved the final document.

Mrs. SCHNEIDER. Well, let me share with you that this particular body is extremely irate about the tendency for Government studies to be accomplished—for us to spend tax dollars—taxpayers' dollars for that purpose and to have those studies receive only limited distribution, and so we are most anxious to ensure that there is a plan for information generation and that we do not have that information gap which seems to be so very typical——

Dr. HECHT. The plan specifically provides for not only a data management system, but a flow of information.

Mrs. SCHNEIDER. Well, we'll be very anxious to look at that part of the study also. And I have no further questions.

Dr. HECHT. Thank you.

Mrs. SCHNEIDER. I commend you on your work, or perhaps I should reserve that until I read the report.

Dr. HECHT. Thank you.

Mrs. SCHNEIDER. Thank you for taking such a massive undertaking, and I think we're all very anxious to see what you and the other agencies have come up with.

Mr. Chairman, thank you.

Mr. SCHEUER. OK.

Let me say that we have with us about a dozen and a half members of the Virginia Military Institute environment class and we welcome you all. The class is taught by Bob Marston, a former president of the University of Florida and former Director of the National Institute of Health, so we're very happy to have amongst us possible—future possible military public policymakers amongst our midst. Welcome, all.

Let me ask just two questions and you can answer them very briefly if you would, Dr. Hecht, and then you might want to elaborate on your answer in—in a memo to us expanding on your testimony.

First, how much funding are you seeking over how long a period of time? And do you need any additional budget help in fiscal 1985, which we're in the process of considering?

Whatever your timeframe is—if it's 5 years or less, what are the milestones by which you and we can judge progress? That's the first question.

The second question is: How would your plan contemplate coordinating the melange, the potpourri, I almost might say, of agencies that are mixing their ladle in the stew? Let me repeat them once again: The Department of Energy; NOAA; the U.S. Navy; the Defense Nuclear Agency; NASA; the National Science Foundation, and FEMA, the Federal Emergency Management Agency. By what magical process are you going to bring order out of what looks to be apparent chaos?

Dr. HECHT. I have three short answers——

Mr. SCHEUER. Good.

Dr. HECHT [continuing]. And I will give you in writing more detail.

First, on money, I must say that, as you can imagine, I'm not—I'm only reporting to you the recommendations of the drafting committee within the plan. It's a 5-year plan and it averages about $10 million a year.

There is an existing amount of resources that are in the Department of Defense and the Department of Energy in their base program to carry on this work; to do the job as envisioned by the drafters of the committee. The extra resources required are as I described, and I can give you more information if you require.

How to bring chaos? Well, as you know, the National Climate Program is an interagency program——

Mr. SCHEUER. No, not how to bring chaos. We all know how you bring chaos. [Laughter.]

Dr. HECHT. Did I say that? [Laughter.]

How to bring order.

Mr. SCHEUER. We better bring order and discipline and reason down——

Dr. HECHT. Freudian slip. As you know, the National Climate Program is an interagency program, so I have some experience in how to deal with that thing, that problem, but in this instance, I must say that I think it's easy. There has been a very strong amount of support across the board from all the agencies that are involved. Defense Department, Department of Energy, NASA, and so on down the line.

Each has their own interest and their own expertise, but the enthusiasm, I think, among scientific levels—and I restrict myself there to people who have helped contribute to drafting the plan and the development of the plan, suggest to me that we have a good basis for proceeding to do the research.

The management will be agreed to, I hope, by the agencies and will be a foundation upon which to carry the work out. Even—I must in all fairness say that OSTP has been especially supportive of the work. I never had a problem in any question getting to talk to Jay Keyworth. I call up, talk to the secretary and tell her it's Ed Teller and I get through right away. [Laughter.]

But I'll provide more information to you in writing.

As far as——

Mr. SCHEUER. Thank you.

Dr. HECHT. As far as the milestones go, I think that can be very explicit because it is defined in the plan, and rather than take more time, I'll submit that in writing.

[The information is available in committee files.]

Mr. SCHEUER. Very good, we appreciate your testimony very much.

Dr. HECHT. Thank you.

Mr. SCHEUER. Dr. Aleksandrov, we appreciate having you here——

Dr. ALEKSANDROV. Thank you very much.

Mr. SCHEUER [continuing]. And we've enjoyed giving you a little example of democracy in action. [Laughter.]

Under our form of government, we have a tripartite form of government: Judiciary, executive branch, legislative branch, and one of the functions we have here in the legislative branch is the oversight function. We supervise the functioning of the executive branch and occasionally we invite them down here—frequently on a very pleasant and friendly basis, and sometimes they come kicking and screaming, but we invite them down here and we ask them all kinds of probing questions and we let them know that we're going to be watching them; we let them know that we expect them to shape up; and that we will be asking them back again in 3 months or 6 months or 9 months to testify on what progress has been made. That's the way our Government works.

You may feel, from this morning's carryings on that it's a very messy, not very tidy process, and I can only quote to you the immortal words of Winston Churchill when he described the untidiness and messiness of democracy and he said: "Democracy is the worst possible form of government, except for all those other forms of government." [Laughter.]

All right, we'll move on.

Dr. HECHT. Thank you, Mr. Chairman.

Mr. SCHEUER. Thank you all for coming. We appreciate your testimony, both of you.

We'll now have the last panel, strategic considerations. Dr. Leon Goure, director of the Center for Strategic Studies, Science Applications International Corp., McLean, VA; and Dr. Ted Postol, Center for International Security and Arms Control, Stanford University in California.

Dr. Goure is currently the director for the Center for Soviet Studies at the Science Applications International Corp. here in Washington and he has, in addition, authored 13 books and numerous articles on civil defense.

Dr. Goure, time is going by very rapidly; we've just been notified they have another hearing that will start in the next 15 minutes or so, so why don't we ask you to summarize your testimony, which will be printed in full at this point in the record, in the next 5, 6, or 7 minutes and then after Mr. Postol has testified, we will have a chance to ask you a few questions.

Please proceed.

STATEMENTS OF DR. LEON GOURE, DIRECTOR, CENTER FOR SOVIET STUDIES, SCIENCE APPLICATIONS INTERNATIONAL CORP., AND DR. THEODORE A. POSTOL, CENTER FOR INTERNATIONAL SECURITY AND ARMS CONTROL

Dr. GOURE. Thank you, Mr. Chairman. I just want to say I appreciate this opportunity and I want to emphasize that I'm here only expressing personal views and certainly not that of either my employer, the Science Applications International Corp., or any research conducted there under contract.

The real key points to be made, I think, are that even if one accepts the uncertainties of nuclear winter and accepts the possibility of nuclear winter being the plausible outcome of strategic exchanges, there are other uncertainties, namely the scenarios. We're talking about the number of weapons that may be detonated, their targets, their yields, the climatic conditions at a time when the detonations occurred, the time of the year and so on. In other words, there are many kinds of possible nuclear winters which vary in severity.

So in that context, they have a different potential impact. One is, of course, that—the question of strategic deterrence. One regrettably must say that nuclear winter does not preclude the possibly or defer fully the possibility of a nuclear war.

We know that exchanges with many thousands of nuclear weapons could occur even—and without triggering the—at least most catastrophic types of nuclear winter.

In the—it has, however, some other strategic implications, possibly at least, such as escalation control. If one is afraid of crossing some sort of nuclear threshold, you will have potentials for some degree of escalation control; therefore, for intrawar bargaining and possibly some sort of negotiated war termination if war were to occur.

Of course, the point is that in order to have that, you have to have the capability of at least threatening each other with a nuclear winter effect throughout the course of the war in order to be able to maintain control.

In the targeting, it has been suggested that since soot is the main problem—that is, from urban fires—either restraint or avoidance of targeting cities is the obvious logical conclusion. Unfortunately, there's a lot of leeway even in that at this time. It is obvious that you can selectively target and it's obvious, also, that targets on the periphery of the cities will not necessarily cause the fires in the central city areas which seem to be so important for a nuclear winter effect.

And there are alternatives. You can use different kinds of methods of attacking targets in cities, such as chemical and bacteriological weapons or detonate small-yield weapons under the surface of the ground to reduce fire effects, et cetera. One of the interesting implications, at least, of strategic—of the nuclear winter is that it seems to lend further rationale to strategic defense. The fewer weapons actually denotated on your territory, the less likely you will have a nuclear winter effect. So, from that point of view, a significant reduction in the number of weapons which may impact seems to at least support a desirability of having that kind of a protection.

In the reduction of yields and stockpiles in the question of yields, I must say it's a practical matter in part that these specific weapons are targeted for specific purposes. they are supposed to accomplish certain missions. If they can be—achieve these missions or intended missions with lower yields, it seems like a reasonable thing to do.

On the numbers, however, when we talk about reduction of stockpiles, Dr. Sagan, in his "Foreign Affairs" article, suggested a limit of 500 to 2,000 warheads to bring the arsenals below what he called the Doomsday Threshold. The problem is that not only are larger exchanges possible, but as he admitted himself, one really doesn't know yet what the threshold is, which nuclear winter threshold are we talking about in the first place?

Two, there is the uncertainty whether the Soviet Union and United States would agree where the thresholds lie or how much of the—the adverse consequences of a nuclear winter they would be willing to tolerate, and finally, if you reduce it to that level, you may make nuclear war safer, or appear safer, and consequently, it would be destabilizing.

Mr. SCHEUER. Dr. Goure, the bells went off since you started testifying——

Dr. GOURE. Sorry.

Mr. SCHEUER. Let me give you one more minute to sum up——

Dr. GOURE. OK.

Mr. SCHEUER [continuing]. And then you can extend your testimony in writing and then I'll ask Mr. Postol to take——

Dr. GOURE. Thank you.

Mr. SCHEUER [continuing]. About 4 minutes and then we'll suspend the hearing.

Dr. GOURE. I just want to make the point that nuclear winter does not negate the utility of passive defense measures and measures to prepare to mitigate the effects of a nuclear winter since there are many kinds of nuclear winters.

And finally, given the present uncertainties about nuclear winter hypothesis as a potential strategic implication, it would be premature for any strategic planner, be it American or Soviet, to be guided by it. The Soviets give no indication of being guided whatsoever, at least in their current public statements about civil defense, about their strategic intention and et cetera.

Now, of course, in the future, this may be different if the hypothesis is confirmed, and it may become a significant factor in the overall factor of strategic planning. Further studies of potential strategic consequences of nuclear winter, therefore, is another matter. I believe that it's worthy of attention and support, but certainly not today to be used—the hypothesis to be used as a reason for changing concepts as yet when we do not know where they actually lead to and so many alternate possibilities are before us.

Thank you, Mr. Chairman.

[The prepared statement of Dr. Goure follows:]

SOME POTENTIAL STRATEGIC IMPLICATIONS OF THE "NUCLEAR WINTER" HYPOTHESIS

It should be emphasized that the following discussion represents strictly the personal views of the author of this paper and in no way should be taken to represent the views of the Science Applications International Corporation or any conclusions drawn from research carried out by its staff.

The authors of the "Nuclear Winter" study, R.P. Turco, O.B. Toon, T.P. Ackerman, J.B. Pollack and Carl Sagan (hereafter referred to as TTAPS), offer an apocalyptic prediction of possible global climatic consequences of a large nuclear exchange. This prediction critically depends on the amount of soot particles, injected into the troposphere by numerous large urban fires which may result from nuclear strikes. Under certain circumstances, the effects on climatic conditions generated by the fire-produced soot may be significantly aggravated and protracted by the amount of fine dust particles lofted into the stratosphere by surface and near-surface detonations of nuclear weapons.

At the present time, as the authors of the TTAPS study acknowledge, there are many uncertainties about the phenomenology underlying the key parameters believed to be essential to produce a "Nuclear Winter." For purposes of this discussion, however, it is assumed that the "Nuclear Winter" hypothesis represents an accurate prediction of what may occur in certain nuclear war conditions. Even so, it is important to note that the "Nuclear Winter" effect is very much scenario dependent. Specifically, as the TTAPS study indicates, whether or not a "Nuclear Winter" occurs, its intensity, duration, and probable consequences depends on a number of variables. In particular these variables include the number of nuclear weapons detonated at a given point in time; their yields and modes of detonation, i.e., whether they are subsurface, surface, near-surface, or air burst; their targets; the number and characteristics of the fires they set; the length of time over which nuclear exchanges are conducted; and the time of the year they occur; as well as the general atmospheric conditions within the belligerent countries when the exchanges take place. Thus, given the many variables, a wide range of scenarios with different possible climatic consequences is theoretically possible. In view of this, any discussion at the present time of possible strategic implications of the "Nuclear Winter" hypothesis for strategic deterrence, escalation control, strategic defense, reduction of nuclear weapon yields and stockpiles, and war survival measures must of necessity remain very tentative and speculative.

1. STRATEGIC DETERRENCE

At first glance it may appear that the predicted "Nuclear Winter" effect, by posing an extreme mutual assured destruction threat, could serve as a very persuasive and effective deterrent to nuclear war. Unfortunately, this does not appear to be the case. As some of the scenarios discussed in the TTAPS study and others one can readily think of, indicate strikes with thousands of nuclear warheads are possible without necessarily triggering a severe or disastrous "Nuclear Winter." For example, in the August 1984 issue of Scientific American an article by the TTAPS group cites the case of a 4,000 megaton counterforce exchange in which all US and Soviet strategic forces as well as command and control facilities are targeted, while strikes on cities are withheld. Such an exchange, they estimate, may have the same climatic consequences as the Tambora and Krakatau volcanic eruptions in the 19th century, i.e., a relatively minimal effect. Furthermore, even if the leadership of the United

States and the Soviet Union were to have the same perceptions of a possible "Nuclear Winter" effect, they would not necessarily hold similar views on what degree of adverse climatic consequences they would be willing to accept. In addition, they also may not have the same perceptions of what conditions cause various "Nuclear Winter" effects, while in turn could result in their holding different views on the consequences of various types of attack. Thus, while concern over a possible "Nuclear Winter" effect may influence how a nuclear war may be fought, it would not necessarily deter such a war from occurring.

The deterrent effect of the "Nuclear Winter" hypothesis may also depend on a nation's perceptions of the magnitude of population losses and damage it expects to suffer from the immediate effects of nuclear detonations and radioactive fallout. For example, it has been claimed that in the event of a large nuclear exchange and in the absence of protective measures for the population, up to 170 million Americans may be killed with additional tens of millions being injured, and there would be no prospect of national reconstitution or economic recovery. Such a projection, based on a "worst case" scenario, would make the additional deterrent threat of a possible "Nuclear Winter" relatively unimportant. Indeed, it can be argued that the significance of the "Nuclear Winter" threat as a strategic deterrent may be directly dependent on the size of the portion of a nation's population and economy which is expected to survive the immediate effects of nuclear detonations and radioactive fallout. The larger this portion is anticipated to be, the greater may be the deterrent influence of a possible "Nuclear Winter." From this point of view, a major asymmetry in US-Soviet civil defense capabilities may be destabilizing. Even so, the threat of inflicting unacceptable losses and damage by nuclear strikes below the threshold which may trigger a "Nuclear Winter" is likely to remain the principal factor in strategic deterrence.

2. ESCALATION CONTROL

In principle, the threat of occurrence of a "Nuclear Winter" at certain levels of magnitude of a strategic exchange may enhance prospects of intra-war escalation control by mutually deterring the belligerents from escalating their strikes into a large counter-city or countervalue exchange. The belligerents may have to exercise considerable restraint in the magnitude and character of their nuclear strikes and great caution in deciding on escalatory steps. This in turn may increase prospects for intra-war negotiations and for a negotiated war termination. The requirement for such escalation control would be the possession by both sides of sufficient survivable strategic capabilities throughout the conflict to credibly threaten each other with possible escalation which may bring about a severe "Nuclear Winter" effect.

In theory, "Nuclear Winter" as a factor for escalation control may also lend itself to less desirable scenarios. For example, the aggressor may deliver strikes whose effects deliberately approach the threshold at which a severe "Nuclear Winter" might be triggered in the expectation of thereby deterring retaliation. The country subjected to the attack would be faced with the dilemma of either withholding its retaliatory strikes or accepting the risk that its retaliation would trigger a "Nuclear Winter" to which itself would fall victim. It is also possible that the threat of causing a "Nuclear Winter" may offer significant opportunities for international blackmail and coercion by a state which either gives the impression that its leadership may be willing to take such a risk in order to attain its objectives or is better prepared than others to mitigate the consequences of a "Nuclear Winter."

3. TARGETING

Given that the key factor producing a "Nuclear Winter" is the soot from large urban fires, the "Nuclear Winter" hypothesis suggests the need for restraint, if not avoidance altogether, in targeting cities with nuclear weapons. This could be a beneficial consequence of the hypothesis. As was noted, it could also be an important factor in escalation control. Of course, the concept of a city avoidance strategy is not new, but the "Nuclear Winter" effect may lend it further rationale and urgency.

It should be noted, however, that a city avoidance strategy does not preclude a large counterforce exchange given that a major portion of US and Soviet military targets are not collocated with or in close proximity to large urban areas. Furthermore, it is generally believed that neither the United States nor the Soviet Union target cities per se, and it is highly improbable that, as some scenarios suggest, they would strike the centers or inner-cities of a great number of large cities given that these usually do not contain significant military or war-support targets. Even today a countervalue attack may be limited to a relatively small number of select critical nodes, whose destruction would effectively paralyze not only much of the war-support industry but also important sectors of the economy. Of course, there may be important installations in a number of urban areas which may be specifically targeted and various cities may suffer collateral damage from strikes on installations on their periphery. The exact implication of such selective strikes for the magnitude of urban fires is not clear and in any event would depend, among other factors, on the yields and modes of detonation of the weapons used to attack such targets.

The point is that avoidance of the "Nuclear Winter" effect does not necessarily mean that no targets in urban areas would be attacked. The TTAPS scenarios do not make clear how many large cities were assumed to have been attacked in order to trigger a severe "Nuclear Winter" effect. If, as one TTAPS scenario claims, a "Nuclear Winter" threshold is represented by strikes with one thousand 100 kiloton weapons on 1,000 large cities, then the belligerents may have considerable latitude in conducting selective strikes on targets in or near urban areas and still remain below this threshold. It should be noted that there are 170 cities in the United States with populations of 100,000 and greater and 276 such cities in the Soviet Union. Even strikes with several weapons on targets on their peripheries will not guarantee the burning of their high-density inner city areas which TTAPS believes to be necessary to reach the "Nuclear Winter" threshold.

Scenarios which assume nuclear strikes on all large European cities do not appear very credible given the military and political restraints on both the United States and Soviet Union. The Soviet Union would not wish to destroy Western Europe, which it hopes to conquer and exploit, and also could be expected to avoid provoking France and Great Britain into launching retaliatory nuclear strikes against Soviet cities. The United States is unlikely to target the large non-Soviet cities of Eastern Europe, and even less so any Western European cities occupied by Warsaw Pact forces.

Even if fear of triggering a "Nuclear Winter" results in restraint in the use of strikes on large urban areas with large-yield nuclear weapons, this need not preclude the belligerents from attacking important political control, war support, or economic installations. One possibility may be to attack such targets with small-yield accurate warheads which would be detonated below the surface of the ground in order to minimize secondary fires. Another may be the use of chemical or bacteriological weapons to interdict the use of important installations or areas and to destroy or incapacitate the work force. Unlike the United States, where the possibility of Soviet strategic attacks with such weapons has been ignored, the Soviet Union pays considerable attention to this threat and devotes significant resources in its civil defense program to the protection of the population and economy against such attacks. Finally, one cannot exclude the possibility of use of advanced types of conventional munitions with lethalities said to be approaching those of nuclear weapons against such targets.

4. STRATEGIC DEFENSE

The "Nuclear Winter" hypothesis appears to enhance the utility of strategic defense of both military strategic and urban targets. In the first instance, given that stratospheric dust produced by the detonation of large-yield nuclear weapons on hard targets such as missile silos slows the return to ambient climatic conditions, the pursuit of damage limitation may be better achieved by the strategic defense of such targets than by counterforce strikes. In the second instance, it would obviously be beneficial if it were feasible to reduce, by means of strategic defense, the number of enemy nuclear weapons which may be detonated in urban areas to below what may come to be accepted as the "Nuclear Winter" threshold.

5. REDUCTION IN WEAPON YIELDS AND STOCKPILES

According to the "Nuclear Winter" hypothesis, the yields of nuclear weapons bear on the amount of fine dust which may be injected into the stratosphere and also on the magnitude of urban and other fires directly ignited by nuclear detonations. The TTAPS study, therefore, suggests that use of lower-yield nuclear weapons may reduce the possible occurrence of "Nuclear Winter" or at least its duration. It appears especially desirable to reduce the yields of individual strategic warheads to less than 1 megaton.

Actually, given present missile accuracies, there are few, if any, targets whose destruction may require strikes with warheads with yields in excess of 1 megaton, and indeed, there appear to be relatively few targets requiring weapons with yields above .5 megaton to attack. Improved accuracies and the introduction of MIRVs have generally resulted in a trend in both the United States and Soviet Union toward lower yields in strategic nuclear weapons. In the case of the United States, the current aggregate yield of its strategic weapons is only one-fourth what it had been in the 1960s. The yields of Soviet strategic warheads, while generally tending to be larger than those of the United States, have also noticeably decreased in the past decade. In the matter of further reduction in the yields of strategic weapons, the question is one of practical consideration in terms of the ability of the weapon to destroy the target sets they are intended to attack. Thus larger-yield weapons are required to destroy hard targets such as missile silos than soft targets such as industrial plants. To the extent that with present or future accuracies the intended strike missions could be achieved with smaller-yield weapons, such reductions might be worth considering.

There has been a general long-standing agreement on the desirability of US-Soviet negotiations leading to a reduction in the size of their strategic nuclear weapons stockpiles. This is the stated objective of the present US administration's arms control policy. It is also recognized that such a reduction could significantly enhance the effectiveness of ballistic missile defense and civil defense in protecting the country from attack. There is, however, considerable controversy over how to achieve this objective, and at present prospects for its attainment are uncertain.

In the context of the "Nuclear Winter" hypothesis, the question is what particular significance it has for such arms reduction. In his Foreign Affairs article (Winter 1983-1984), Dr. Carl Sagan urged a drastic reduction of the existing stockpiles to below what he called the "Doomsday Threshold," that is, below the level where the use of the weapons could trigger what he characterizes as "the climatic catastrophe." However, what precisely this threshold might be is uncertain and depends on many variables. Dr. Sagan has suggested that it might be in the range of 500 to 2,000 warheads. However, the TTAPS scenarios suggest that the number of weapons could be significantly larger depending on their yields and targets, especially if restraint is exercised in strikes on cities. Furthermore, it is uncertain whether Americans and Soviet planners would necessarily come to similar views on where this threshold lies.

While the concept of avoiding a "climatic catastrophe" by reducing strategic nuclear weapons stockpiles to some level below the "Nuclear Winter" threshold appears attractive, it may have the effect of making the waging of nuclear war seem "safer" to contemplate. It may be argued that rather than reducing the stockpiles below such a threshold, effective deterrence of nuclear war may be enhanced by the possession by both the United States and the Soviet Union of capabilities to threaten each other with "Nuclear Winter." After all, for years many people have equated strategic stability and effective deterrence with the capability of both superpowers to threaten each other with mutual assured destruction. It could be argued, therefore, that the mutual threat to cause a "Nuclear Winter" may be equally or even more stabilizing and deterring. Furthermore, such a capability may enhance prospects for restraint in the use of nuclear weapons in the event of a war and for intra-war escalation control and negotiations. Thus, at least for the present, the "Nuclear Winter" hypothesis does not provide an obvious answer to the question concerning the level to which strategic nuclear weapons stockpiles could be safely reduced.

5. WAR SURVIVAL MEASURES

At the present stage of its development, the "Nuclear Winter" hypothesis does not negate the utility of passive defense measures and preparations aimed at mitigating the consequences of the prompt effects of nuclear detonations as well as of "Nuclear Winter." There are various reasons for this.

First, as was noted, unless significant elements of the nation's population are protected against and survive the prompt effects of nuclear detonations and radioactive fallout, and possibly also chemical and bacteriological attacks, the predicted subsequent "Nuclear Winter" effect may be largely academic from the standpoint of national survival.

Second, any "Nuclear Winter" effect would be certain to cause more damage to the country which is unprepared to mitigate its consequences for the population and the economy, than to the country which has made such preparations. An asymmetry between belligerent countries in civil defense capabilities and preparedness may result in different levels of damage to them and also in different perceptions of the consequences and acceptability of various degrees of severity of "Nuclear Winter."

Third, as the TTAPS study shows, the severity and duration of the "Nuclear Winter" vary and are very much scenario dependent. One need not _a priori_ assume that only the worst case TTAPS scenario is the most likely one. In other scenarios the adverse climatic conditions, if they occur, may be far more survivable, especially if appropriate preparations are made for such contingencies. Furthermore, if the "Nuclear Winter" is a realistic threat, it is not unreasonable to assume that the belligerents would be likely to exercise restraint in their use of force and in the choices of targets; this in turn would increase the effectiveness of civil defense and other disaster mitigating measures.

Fourth, in the matter of the ecological consequences projected in the "Nuclear Winter" hypothesis, the TTAPS scenarios assume the start of the nuclear exchange to take place in June. In other words, they assume a worst-case situation in which the ecology in the northern and mid-latitudes of the Northern Hemisphere would suffer maximum damage from a sharp decline in air temperatures and reduction in the amount of sunlight reaching the Earth's surface. However, presumably a less damaging situation to the belligerents would occur if the strategic exchange were to take place when the plants in those latitudes are dormant, ie., in winter. In the TTAPS baseline scenario, return to near ambient sunlight and above freezing air temperatures in the interior contaminated areas are projected to be reached in some 100 days or less. If fewer cities burn than is assumed in the scenario, a return to near ambient sunlight conditions would occur even sooner, and if there is less dust in the stratosphere, the duration of lower temperatures would be shorter. In other words, the worst conditions would not last much longer than the winter. Indeed, given that in the first year after an exchange prospects for agricultural production the belligerent countries will be poor for reasons of disruption of the economy, if not because of some sort of "Nuclear Winter" effect, it would be logical for an aggressor to initiate his attack only after he has harvested his crops and not before as the TTAPS scenarios assume. An attack in that season of the year would have also the advantage that probable meteorological conditions in the belligerent countries, ie., snow, rain, fog, overcast, etc., would tend to mitigate the secondary effects of nuclear detonations such as fires and also increase the rate of rainout of soot and dust in the troposphere. With adequate food stocks and preparations, a country may be able to feed and sustain its surviving population through a year of adverse climatic conditions while preparing to reconstitute essential agricultural production. In his Foreign Affairs article Dr. Sagan acknowledges that this may be a possibility, although he mentions that the "breakdown of civil order and transportation systems" may prevent effective support of the population. Such a "breakdown," however, is by no means inevitable, although whether or not it occurs will depend in a large measure on the effectiveness of pre-attack civil defense planning and preparations. Certainly the Soviet civil defense program expects to ensure both civil order and an organized system of support of the population in the post-attack period. Mention is also made of other possible adverse effects on the ecology such as global radioactive fallout, depletion of the ozone layer, and so forth; however, these are largely independent of the "Nuclear Winter" hypothesis.

Given the many current uncertainties about "Nuclear Winter" and its potential strategic implications, it would be premature for any strategic planner, be he American or Soviet, to be guided by this hypothesis. Indeed, the Soviet approach to this question is illustrative. Soviet propaganda, as reflected by political and science spokesmen, has enthusiastically embraced the TTAPS "Nuclear Winter" hypothesis as well as other Western "worst case" nuclear war scenarios in order, as is publicly acknowledged, to influence Western public opinion and US defense programs. The official Soviet public support for the TTAPS hypothesis, however, has had no visible effect on Soviet defense policies. Thus, in recent times, Soviet scientists have been instructed by the leadership to work even harder on the further strengthening of Soviet military might; Soviet military chiefs predict a further build-up of Soviet offensive strategic nuclear weapons; and the utility of Soviet civil defense and the need to further perfect it continues to be extolled.

Of course, if additional studies and analyses confirm the "Nuclear Winter" hypothesis as constituting a realistic possibility, it is possible that eventually this may significantly influence strategic planning and weapons programs, as well as arms control negotiations. However, to use this hypothesis for such purposes at this time, as some are attempting to do, would seem to be unwarranted.

Mr. SCHEUER. Thank you very much.

Dr. Postol.

Dr. POSTOL. Thank you.

Dr. SCHEUER. About 4 minutes and then——

Dr. POSTOL. Yes, thank you.

Mr. SCHEUER [continuing]. We'll suspend.

Dr. POSTOL. As the Assistant for Weapons Technology in the Office of Chief of Naval Operations from 1982 to 1984, it was my duty to identify the technical issues that have policy implications for Navy and national nuclear programs. Because I supported the Chief in his role as a member of the Joint Chiefs of Staff, I was directly involved in detailed analysis of Soviet antiballistic missile systems, the closely spaced based MX, the President's strategic defense initiative, the Trident weapon system, nuclear war planning, and the like. For this reason, I think I may have some useful comments to make today.

I will try to make three separate and distinct points in my testimony. Two of these points, I believe are profoundly important for national policy. The third point is a technical detail that I just put in because I think it is of interest to the subcommittee.

The first point is as follows: There are many nuclear weapons effects, in addition to the nuclear winter effect, that we do not understand sufficiently. Even if a nuclear winter effect did not exist, our lack of knowledge of many other nuclear effects is so profound that other discoveries could just as well result in drastic changes in our military planning and our national policy.

Now, for the second point. The entire structure of our current nuclear policy is beset by misconceptions and problematic and contradictory features. The policy does not adequately emphasize the role of uncertainty, the scale of risks and consequences, the vagaries and unpredictability of warfare, nor the dangers of requiring decisive action in circumstances where time and information is inadequate.

This policy may, therefore, require considerable reevaluation whether a nuclear winter effect exists or not. It is very unclear how the discovery of a nuclear winter effect will further modify its structure.

Now, for the third point which, as I indicated, is a technical detail. It is almost certainly possible to construct a nuclear force that could credibly by used to threaten the Soviet society with complete destruction, probably without causing a nuclear winter effect.

A discussion of this technical detail, as well as other equally relevant technical details, are contained in my written testimony. As a military planner, I would like to emphasize that the acquisition of such a winterless nuclear force would in no way resolve the profound and imponderable military security issues that we confront today. It would still be the overwhelming threat of escalation; it would still be the unimaginable weight of any execution decision; there would still be the many incalculable effects and unknowns of warfare, and the enemy could always choose to guarantee that our society will also die.

For this reason, my remarks, which I will have to brush over, mainly focus on the national policy questions and the nuclear weapons effects uncertainties, which I would like to point out, has driven our national policy in the past, based on many misconceptions we had at an earlier time about other nuclear weapons' effects.

[The prepared statement of Dr. Postol follows:]

Possible Military and Strategic Implications of Nuclear Winter

Statement of Theodore A. Postol
Center for International Security and Arms Control
Stanford University

Thank you very much for the opportunity to appear before your subcommittee to discuss this question of still another possible and previously unforeseen effect of nuclear war.

As the Assistant for Weapons Technology in the Office of the Chief of Naval Operations between 1982 and 1984, it was my duty to identify technical issues that have policy implications in both Navy and National nuclear programs. Because I supported the Chief in his role as a member of the Joint Chiefs of Staff, I was directly involved in detailed analysis of Soviet Anti-Ballistic Missile systems, the Closely Spaced Based MX System, the President's Strategic Defense Initiative, the TRIDENT weapon system, nuclear war planning, and the like. For this reason, I believe I may have some useful thoughts to share with this subcommittee on possible strategic and military implications of nuclear winter.

There are three separate and distinct issues I will be addressing in my testimony today.

First, I believe that there might be significant and profoundly important changes in nuclear strategic planning that could be dictated when and if our understanding of the nuclear winter phenomenon matures. However, although I will be giving examples of planning issues in this testimony, I must emphasize that uncertainties in nuclear planning, as well as in our understanding of many nuclear phenomena are very large. Even if a nuclear winter effect did not exist, our lack of knowledge of many nuclear effects is so profound that other discoveries could just as easily result in drastic changes in our military planning and in our concept of deterrence[1]. As a consequence, the examples of military planning issues I will discuss today may not be those of greatest concern at some future date.

Second, as I will try to explain in my testimony, our current nuclear policy is beset by problematic and contradictory features, and therefore may require considerable reevaluation whether a nuclear winter effect exists or not. For this reason, it is very unclear how the discovery of a nuclear winter effect will further modify its structure.

Finally, I will propose an approach to military planning that is likely to dramatically reduce or eliminate the effects of nuclear winter phenomena. However, I want to emphasize that this approach to military planning would not necessarily result in a more stable world than the one we live in today.

The current defense strategy of the United States requires that our nuclear forces have the ability to destroy Soviet society, as well as to retaliate at any level of conflict in a deliberate and selective way. The stated objective of this strategy is to provide American leadership with forces that could be used to deny any advantage to the Soviets at any level of conflict[2]. In the remainder of my testimony, I will refer to this approach to achieving deterrence as our current strategy.

Given this strategy, there are three broad strategic and military questions raised by the threat of a nuclear winter:

1. Does the possibility of a nuclear winter effect from massive urban/industrial attacks alter the Soviet-U.S. deterrent relationship?
2. Are there interesting technical and military factors associated with this effect that should be addressed?
3. Are there interesting quantitative and/or qualitative threshold effects that make certain kinds of militarily interesting limited nuclear attacks more or less plausible?

On the question of the mutual assured destruction relationship, four points are worth consideration.

1. At this time, the scale and consequences of nuclear winter effects is highly uncertain, even for massive urban/industrial attacks.
2. If the effect does in fact occur, massive attacks on cities would not only be homicidal but they would also be suicidal.
3. However, only a very small fraction of both U.S. and Soviet forces could destroy the other's cities. Hence, either country could readily retaliate against the other's cities in almost any imaginable circumstance, guaranteeing that a massive city attack by one side on the other would be suicidal anyway.
4. It is technically possible for the U.S. to build nuclear forces capable of threatening the destruction of Soviet cities while limiting nuclear winter effects.

Later in this testimony, I will expand on this point considerably.

On the question of technical and military factors: there are many technical affects that are significant in a narrowly military context that should be studied. However, the discovery of a possible nuclear winter effect should not have been necessary to get these issues properly addressed. These questions are:

1. Are there interesting and significant effects of smoke and atmospheric changes on infrared early warning and reconnaissance systems (see figures 15 and 16)?
2. Are there still other systems, like optically aided ABM systems and defense radars that would not work as planned in an atmosphere perturbed by the presence of optically absorbing high altitude particulates (see figures 12 through 14)?
3. Are there more accurate ways of predicting unintended damage so that attacks that are said to be "limited" are in fact limited?
4. If not, can the uncertainties in possible levels of unintended damage be quantified more systematically, so non-technical decision-makers can better appreciate the range of consequences and uncertainties that might accompany the execution of any limited attack?
4. Are there ways of assessing the true affects of attacks on an enemy's military and social infrastructure, by accounting for the fragile and organic nature of industrialized societies and mechanized forces?

A better understanding of these technical issues could have profound significance for policy makers.

For example, how many weapons do we really need to meet the country's various military objectives? Does the President really have an accurate picture of the consequences and uncertainties associated with any given execution order? If we are forced to execute a limited nuclear attack in response to Soviet aggression, could the objective of the attack be achieved with many fewer weapons than we would now use? Would an arms control treaty limiting us to 1000 warheads allow us to plan for all the military contingencies of concern to our leadership, or do we require 20,000 warheads?

If we find that the nuclear winter effect only occurs for very large, relatively indiscriminant levels of nuclear conflict, then the threat of this effect will not change the nature of the policy issues raised by the possibility of limited nuclear war. These policy issues remain to be resolved whether a nuclear winter effect exists or not.

The current strategy does, however, depend heavily on the ability to threaten a wide variety of limited and general nuclear attacks. Thus, assuming the above policy questions were in fact resolved, the following additional questions would have to be added to this list of imponderables:

1. If the nuclear winter effect occurs in a graduated way, rather than at some relatively sudden threshold, are there limited nuclear attacks that then appear to be more or less interesting?
2. Are these attacks really as limited as some people argue?
3. Are there uncertainties that are peculiar to the nuclear winter phenomenon that might be exploitable by either the Soviet Union or the U.S., but not by

both?

4. If so, are there technical solutions that could be adopted by one side or the other as a means of removing or enhancing such assymmetries?

Without a much more solid base of scientific research on the nuclear winter effect, a serious analysis of these policy issues would be meaningless. I would therefore urge the members of the subcommittee to keep these issues in mind, but to recognize that they cannot be resolved until our understanding of this phenomenon is far more complete.

I would now like to turn to the question of how the nuclear winter effect might result in a modification of the country's nuclear strategy. As I will try to make clear, the technical requirements of our current strategy poses many more fundamental questions than those posed by a possible nuclear winter phenomenon.

The current nuclear strategy basically models nuclear warfare as a chess game between two reasoning informed adversaries, both of whom understand and agree to play by the rules of chess. For this model to apply, two underlying assumptions that apply in chess, must also apply in nuclear warfare. They are:

1. Both players can execute and absorb a wide range of limited and general nuclear attacks.

2. Both players can recognize and assess the objectives of these attacks and respond in a measured and graduated way with appropriate counterattacks.

Disregarding questions of irrationality, our current approach to deterrence could only work if the following technical capabilities are in place:

- Both the U.S. and Soviet Union must be able to absorb a limited attack from the other without losing the ability to respond in a controlled and limited manner.

- In order to analyse the enemy's attacks, as well as the success of counterattacks, both sides would need astonishingly capable warning, surveillance and communications systems to provide information on the scale, size and success of attacks and counterattacks.

- Both U.S. and Soviet command authorities and their nuclear forces, as well as the warning, surveillance and communications systems would have to survive throughout the period of conflict.

- The last resort ability to threaten the adversary's society with destruction must exist and be credible.

As I hope I have made clear, the assumptions and technical requirements that accompany our current nuclear strategy raises many fundamental questions. For this reason, nuclear winter or not, there is good reason for the Congress to question the basis of much of the "theory" upon which our nuclear planning is supposed to be based.

However, if the rationale for U.S. nuclear force planning remains unchanged, I do not believe nuclear winter phenomena will necessarily pose planning problems that are significantly more problematic or contradictory than those we already face.

Let me close my testimony by giving an example of how, even if we really were worried about a nuclear winter effect, we could still threaten the Soviets with the maximum possible attack.

I will now describe an approach to nuclear planning that would result in nuclear forces that could be used to threaten an enemy's society with essentially complete destruction, but would probably not cause a nuclear winter effect. By supplementing this force with a moderate number of strategic warheads of today's standard yields, I could make this force very effective in accomplishing essentially all the military missions contemplated for strategic forces today, and I could probably also use it in many applications that are usually not contemplated for todays forces.

Figures 1 through 8 attached to my testimony shows the scale of possible damage effects due to a nuclear attack utilizing a 100 kiloton detonation projected onto a map of Washington. I have chosen this example because the scale of distances is intuitively understandable to all those familiar with this city. As should be evident from the diagrams and text, the consequences of such an attack could hardly be considered to be limited.

Depending on assumptions about height of burst, visibility, and weather, an area of from 14 to 40 square miles could be consumed in mass fires following such an attack. According to the estimates of Turco et al [3] the detonation of 1000 such weapons could possibly result in the massive injection of enough smoke that a climatic catastrophe would follow in days. Hence, an attack involving a thousand or so such warheads against Soviet urban/industrial targets would be suicidal, and therefore isn't credible.

However, by the end of the century, the precision of ballistic missile accuracies could be even finer than the very considerable accuracy available today[4]. Accuracy of weapon placement would then be good enough that very low yield weapons could then be used to attack targets of interest.

Figure 9 shows the area that would be subject to enough heat from the fireball of a 2 kiloton air burst that fires would be likely. This area is about one square mile.

If the attacking nuclear weapon is instead a one kiloton earth penetrating warhead, then the range of severe blast effects could be reduced to about half that shown in figure 9, and the range at which the fireball would ignite fires would be reduced to hundreds of feet.

Thus, the area in which fires would be initiated by the hot nuclear fireball would be reduced to less than a hundredths of a square mile, or less than a thousandths of that which might be set on fire by a single 100 kiloton weapon. If a thousand 100 kiloton weapons falling on cities would cause a climatic catastrophe, then it might now be argued that a million of the smaller weapons would now be required.

This argument is, of course, seriously misleading. Violent explosions often initiate many fires due to static electric discharge from collapsing walls, or from electrical or gas lines. If not extinguished, these fires can do tremendous and extensive damage in a target area.

For example, after the San Francisco earthquake of 1906, there was no means to fight some 30 odd scattered fires. These fires eventually spread, destroying the entire city. For this reason, the use of these very low yield weapons would be accompanied by a considerably larger environmental threat from fire than my early calculations would lead some analysts to believe.

In addition, if the one kiloton earth penetrator was the weapon used in the attack, one could have very high confidence that fires could not be fought in target areas. Since these weapons penetrate into the ground and detonate, the fallout they create is in the form of very large particles which fall very close to the area of the blast. The area immediately surrounding the detonation point would have activity levels perhaps as high as 10,000 rads per hour, delivering a lethal dose of radiation every three to four minutes to those in the open.

However, the many scattered fires initiated in this manner, could have different properties from those initiated in the single flash of a 100 kiloton weapon. Also, the debris cloud following the detonation would not necessarily provide the large upward moving chimney of air through which burning debris could send its smoke. The effects of many fires might then be confined to low altitudes, where scavenging and atmospheric mixing would remove the smoke rapidly. This, of course, is speculation, not an assertion.

An additional feature of this type of attack is the extremely intense but very local fallout. As already noted, very high levels of early fallout would occur in the immediate target area, and very high levels of fallout could also occur at distances as great as five to ten miles downwind of the target area (see figures 10 and 11). However, this fallout would not be a worldwide threat, although it would be highly lethal or injurious to those downwind who could not escape or find shelter. Hence this fallout would not result in a delayed threat against the attacker.

An attack of many such one kiloton earth penetrating weapons could selectively destroy water supplies, power stations, rail and highway junctures, even major hospitals or food storage sites. The result, within days, would be millions of casualties from massive thirst and starvation, followed by the dissolution of the adversaries society. Thus, I have postulated a force capable of destroying Soviet or American society without bringing about an environmental catastrophe.

Although I have described this hatefully shocking approach to nuclear planning, I want to emphasize that I do not advocate the acquisition of such forces.

The acquisition of such forces would not resolve any of the profound and imponderable dilemmas that we confront today. There would still be the overwhelming threat of uncontrolled escalation. There would still be the unimaginable weight of any execution decision. There would still be the many incalculable effects and unknowns of modern warfare. Will our ultra accurate system fail while the enemy's does not? Is the reliability of the systems really what the engineers believe it to be? Will the attack really deal a sufficiently mortal blow to the enemy that we ourselves could avoid destruction?

I have sought to illustrate for this subcommittee some of the technical ways one could avoid a nuclear winter effect, if it were a high enough priority. I have also tried to point to nuclear planning issues of vital importance to this countries military security.

A nuclear war that touches this nation, even if it is of very limited extent, is likely to be the most terrible thing that we have ever experienced. While I in no way wish to diminish the terrifying prospects of a nuclear winter, I have never felt too rosy about nuclear war without nuclear winter. It is my sincerest hope that both these subjects of speculation remain so forever.

I would like to thank the committee for your time and patience.

References and Comments

1. For example, very recent experience with volcanic dust clouds after the Mt. Saint Helens and Galunggung eruptions suggest that under certain conditions relatively low concentrations of very fine dust raised by nuclear explosions can cause severe damage to airplane engines, perhaps five or ten hours after a large scale attack.

Dust from nuclear debris clouds could, in the immediate hours after a nuclear attack, present a serious hazard to airborne command posts and radio relays, bombers and tankers, and cruise missiles. In addition, radiation levels associated with the dust would be very high, possibly even high enough to affect the performance of avionics equipment.

The possible implications of this environmental hazard in military planning are numerous. The United States has a system of airborne communications relays called the Post-Attack Command and Control System (PACCS) which has the mission of maintaining communications by line of sight radio transmissions between aircraft. Because these aircraft can loiter at about 30,000 feet, they can directly communicate with each other using line-of-sight ultra-high frequency radio. Radioactive dust spreading from nuclear detonations could present a major hazard to these aircraft and their crews.

It is also possible that dust raised over the Soviet Union by U.S. SLBM and ICBM attacks could persist sufficiently long that U.S. cruise missiles and bombers would be threatened. This would, of course, depend unpredictably on weather conditions and the nature and scale of attack. It is also worthy of note that Soviet interceptors may not have an easy time operating in this environment either.

2. For a discussion of these points see:
Countervailing Strategy Demands Revision of Strategic Force Acquisition Plans
General Accounting Office Report to the Congress, August 5, 1981

Also: FY 1985 Report of the Secretary of Defense Casper W. Weinberger
Pge 29

But while we work to preserve deterrence, we must also think about and plan against possible failures of deterrence. If deterrence should fail, we cannot predict the nature of a Soviet nuclear strike nor ensure with any certainty that what might begin as a limited Soviet attack would remain confined to that level. We must plan for flexibility in our forces and in our options for response, so that we might terminate the conflict on terms favorable to the forces of freedom, and reestablish deterrence at the lowest possible level of violence, thus avoiding further destruction. Of course, this concept of seeking to enhance deterrence and to limit the level of destruction by having flexible and enduring forces is not new. It has been squarely in the main stream of American strategic thinking for over two decades.

3. R. P. Turco, O. B. Toon, T. P. Ackerman, J. B. Pollack, and C. Sagan
Nuclear Winter: Global Consequences of Multiple Nuclear Explosions
SCIENCE, Volume 222, pp. 1283-1292

4. The author assumes that inertial guidance systems may be enhanced by terrain recognizing sensors, or radio beacons, or star trackers, or sensing of passive satellites, etc.

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EXPERIENCE

1982-1984

Assistant for Weapons Technology
Office of the Chief of Naval Operations
Strategic and Theater Nuclear Warfare Division
The Pentagon
Washington, D.C. 20350

Principal advisor to the Chief of Naval Operations on ICBM/SLBM vulnerability, including Air Force Closely Spaced Based (CSB) MX deployment, Defense Against Ballistic Missile Technologies, SIOP applications of Navy and Air Force systems, and Navy requirements for reentry systems, penetration aids, targeting and SLBM operational concepts. Responsibilities include monitoring developments in arms control negotiations, Soviet and U.S. ballistic missile defense systems, strategic anti-submarine warfare, strategic command, control and communications, and advanced sensor technologies. Duties also involve participation and/or review of activities within The Joint Chiefs of Staff, The Strategic Systems Projects Office, The Defense Nuclear Agency and The Strategic Submarine Division (in the Office of the Chief of Naval Operations).

1980-1982

Analyst
Congress of the United States
International Security and Commerce Program
Office of Technology Assessment
Washington, D.C. 20510

Identify and analyze technical and policy issues central to the problem of MX basing. Technical issues included strategic communications, missile performance characteristics, weapons effects, and evaluation of missile and submarine guidance systems.

Special responsibilities included studying problems of sea basing. This included detailed evaluation of strategic anti-submarine warfare, satellite and airborne surveillance techniques, surface ship and submarine force management. Job included public and secret testimony to Committees of U.S. House and Senate as well as discussions with members of Congress and their staffs. Much of the data was collected directly from defense contractors, research laboratories, and military organizations, including Lockheed Space and Missile Systems, Lawrence Livermore Laboratory, Naval Underwater Systems Laboratories at Newport and New London, Strategic Air Command Headquarters (USAF), Strategic Systems Planning Office (USN), Naval Intelligence Support Center, Central Intelligence Agency and various groups within the Pentagon.

Wrote chapters on Small Submarine Basing of MX, Surface Ship Basing of MX in OTA report MX Missile Basing.
Co-authored chapter on Strategic Command, Control, and Communications
Wrote classified annex on Strategic Anti-Submarine Warfare (SECRET NOFORN)

1978-1980	Assistant Physicist, Solid State Science Division
1975-1978	Postdoctoral Appointee, Solid State Science Division Argonne National Laboratory, Argonne, Illinois

Responsible for the development and management of research program on dynamics of atoms in liquids. Responsibilities included designing and building equipment for neutron scattering experiments, supervision of graduate and undergraduate students and technicians. Additional responsibilities included writing internal status reports, publishing results of research in scientific journals, giving talks at other scientific institutions. Research included collaborative work with workers at Brookhaven National Laboratory, University of Missouri Research Reactor, M.I.T., and University of Chicago.

Published one book and numerous scientific and general interest articles.

EDUCATION

Ph.D., 1975	Massachusetts Institute of Technology Cambridge, Massachusetts
S.M., 1971	Massachusetts Institute of Technology Cambridge, Massachusetts
S.B., 1967	Massachusetts Institute of Technology Cambridge, Massachusetts

AWARDS

NSF Fellowship 1967-1968

NSF Fellowship 1968-1969

A. P. Sloane Fellowship 1971-1972

NATO-NSF Summer Study Grant to attend NATO Advanced Study Institute on Photon Correlation and and Light Beating Spectroscopy, Capri, Italy, 1973

Elected to Sigma-Xi 1973

APPENDIX OF FIGURES

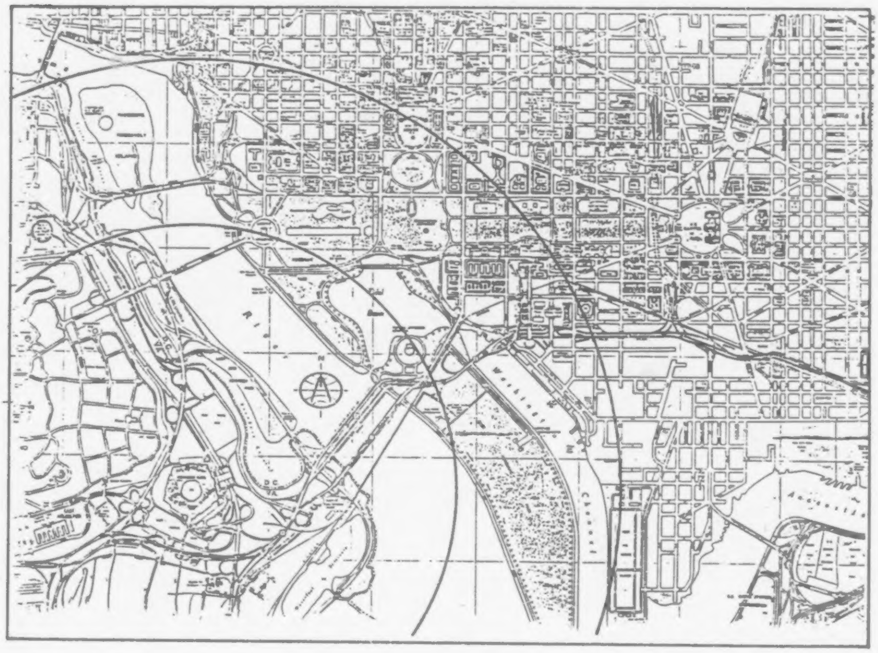

Figure 1.

The circular contours shown on the above map of Washington show the ranges within which significant damage could occur from the blast and fire effects of a 100 kiloton near surface detonation on a clear day. The inner contour is the range at which the shock wave has an overpressure of 5 pounds per square inch or higher. This would be sufficient to knock down most wood frame buildings but would probably only do heavy damage to concrete reinforced buildings of the type that house Government offices. The outer contour shows the range at which 10 calories per square centimeter or more heat from the fireball is deposited. Since ten calories per square centimeter is sufficient to start many simultaneous fires, the area enclosed within this contour would likely be destroyed by mass fire.

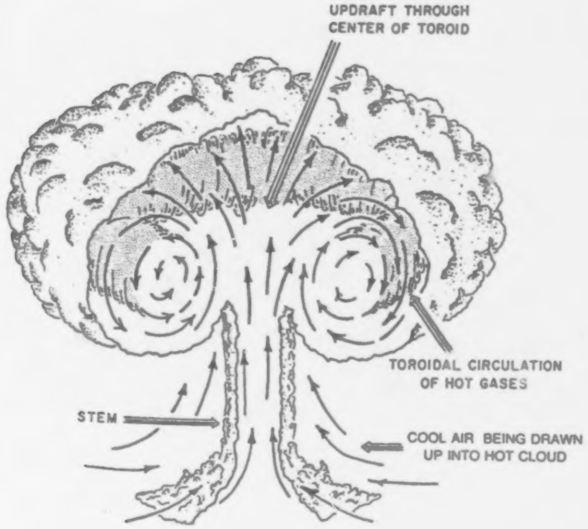

Figure 2.

Cutaway showing an artist's conception of the chimney like air flow following the detonation of a nuclear weapon near the earth's surface. Since the detonation occurs near the surface, the very hot fireball vaporizes material from the target and the nearby surrounding area. In addition, the sudden differential heating of clumps of earth, rock, and sand by the hot fireball, followed by the passage of a violent shock wave, creates large amounts of dust in the target area. Much of this material is swept from the ground by very intense afterwinds.

As these winds carry the dust aloft, the rotating toroidal air flow within the rising hot fireball draws the dust into the fireball's center and mixes it with cooling radioactive bomb debris. Within the fireball, some of the cooling bomb debris will condense into very fine droplets, but much of it will instead "plate-out" onto these dust particles. Because many of these particles are relatively large, they can fall to the ground over periods of minutes or hours, transporting substantial amounts of radioactive bomb debris with them.

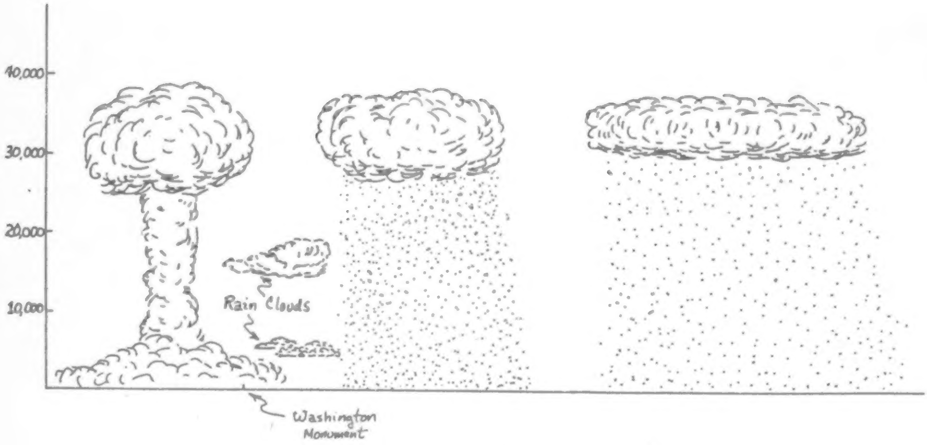

Figure 3.

Within 24 hours of the detonation, from 40 to 70% of the immense radioactivity in the cloud can be carried to the ground by the dust described in the text accompanying figure 2. The size of the cloud of radioactive dust from a 100 kiloton burst can be appreciated by noting that the Washington monument, depicted at approximately 2 miles from the detonation point, is represented as small line to the right of the 40,000 foot "mushroom" cloud. Also shown are commonly occurring cumulus and cumulonimbus rain clouds.

Five to ten minutes after the detonation, the cloud will be close to stabilization, with its top at nearly 40,000 feet. The radioactive debris that has been carried aloft continuously drops out of the cloud as the winds carry it along. Figures 4 and 5 illustrate the approximate size of the area that could be severely contaminated by this dust.

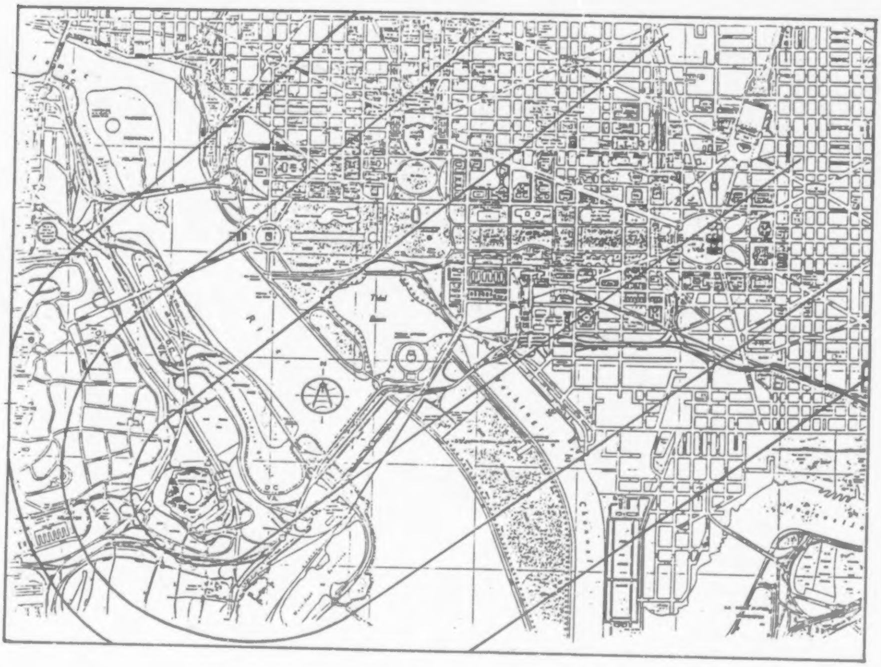

Figure 4.

The approximate contours within which high levels of radiation would develop if south westerly winds blew the debris cloud over the city is shown above. The inner contour encloses an area where 500 to 1000 rads per hour or more could be expected shortly after the attack. The next most inner contour shows the 150 to 300 rad per hour contour and the outer line shows the 50 to 100 rad per hour iso-dose rate contour.

Because the radiation level drops very quickly, unprotected individuals would not receive a lethal dose in as short a time as one might expect from these contours. However, evacuation or protection for the population within these regions would be required within fractions of an hour to hours of the attack.

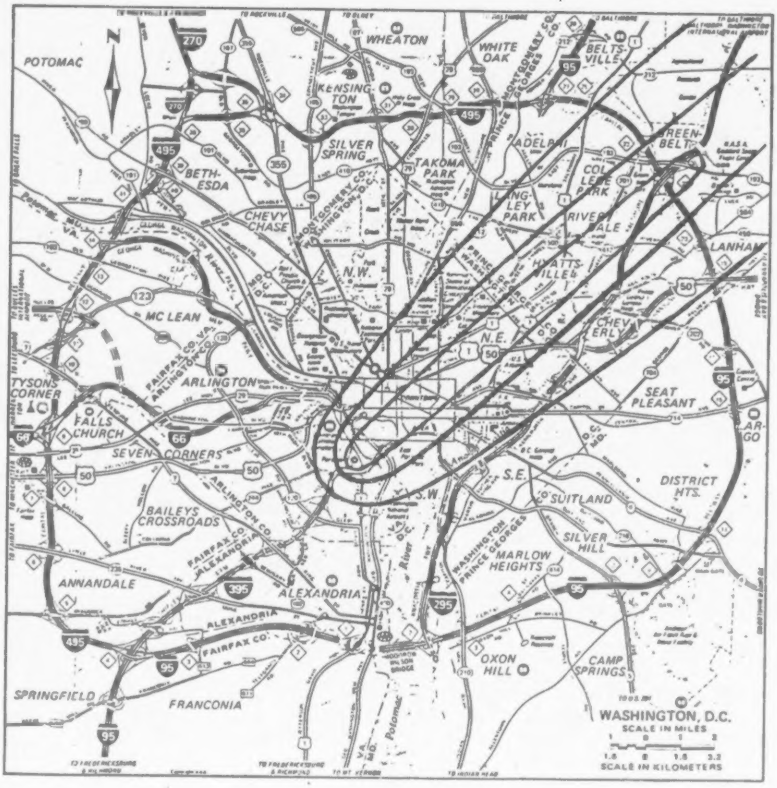
N
POTOMAC
WHEATON
WHITE OAK
BELTSVILLE
KENSINGTON
SILVER SPRING
TAKOMA PARK
ADELPHI
GREENBELT
BETHESDA
CHEVY CHASE
COLLEGE PARK
LANGLEY PARK
RIVERDALE
LANHAM
MC LEAN
N.W.
HYATTSVILLE
N.E.
CHEVERLY
ARLINGTON
TYSONS CORNER
FALLS CHURCH
SEAT PLEASANT
LARGO
SEVEN CORNERS
S.E.
DISTRICT HTS.
S.W.
SUITLAND
BAILEYS CROSSROADS
SILVER HILL
MARLOW HEIGHTS
ANNANDALE
ALEXANDRIA
OXON HILL
CAMP SPRINGS
SPRINGFIELD
FRANCONIA
Potomac River
WASHINGTON, D.C.
SCALE IN MILES
SCALE IN KILOMETERS

Figure 5.

The extent of the area of possible severe contamination could be very large. The three above contours show the one hour reference time dose rate contours of 1000 (inner-most contour), 300 (middle contour), and 100 (outer contour) rads per hour. This defines a region where individuals would have to be evacuated or sheltered if they were to avoid death or serious injury from exposure to radioactive dust from the fallout cloud described in figures 1 through 4.

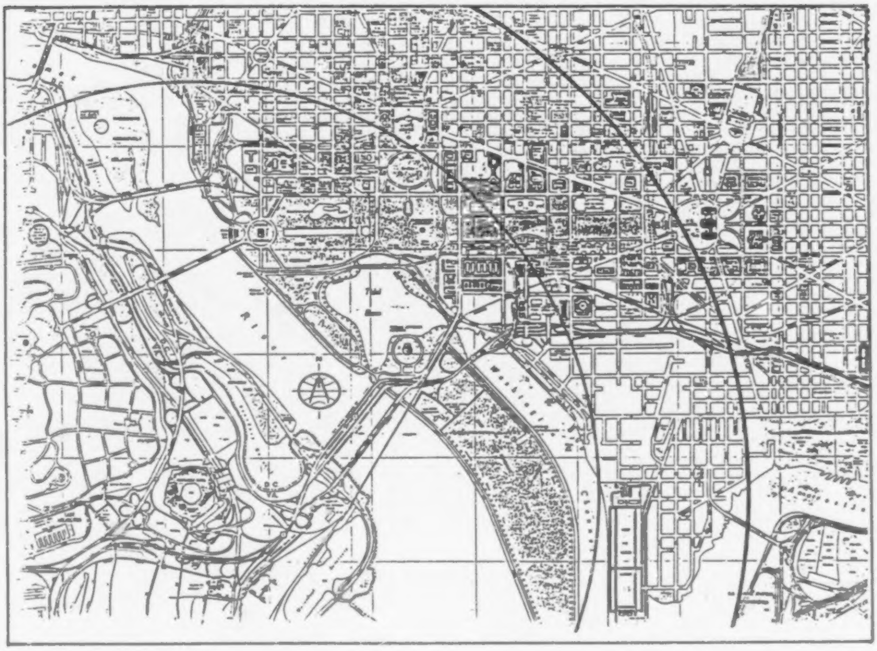

Figure 6.

The above diagram serves to illustrate how the blast and thermal damage ranges described in figure 1 increase when an air burst of altitude about 1000 feet is chosen rather than a near surface burst. By detonating the weapon at or slightly above this altitude, the early fallout described in figures 2 through 5 can be avoided. However, the range at which mass fires and severely damaging blast effects occur is increased.

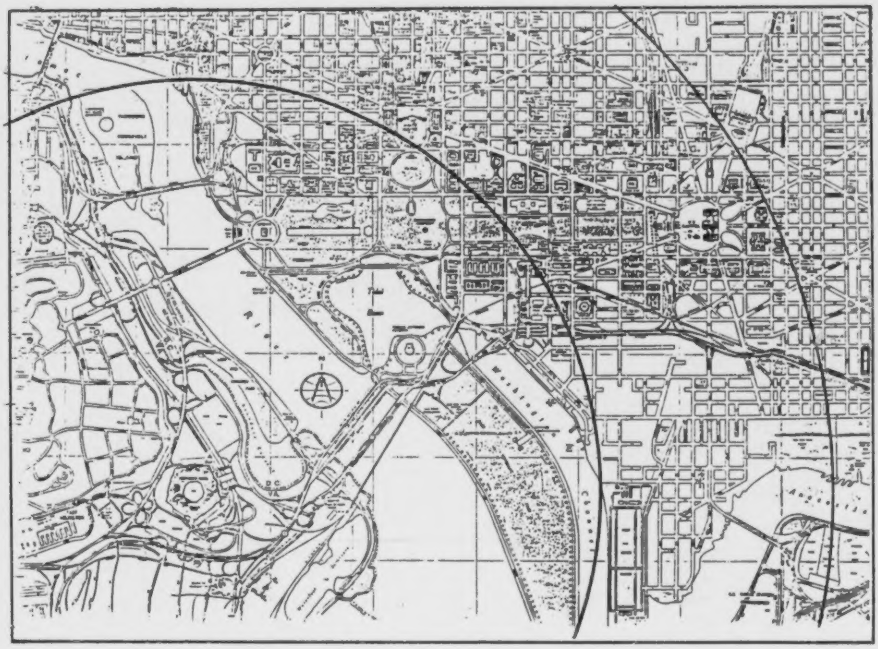

Figure 7.

The increase in range at which mass fires could occur from an airburst of the type described in figure 6, but on a clear but cloudy day, is shown above. Since the postulated detonation would occur below the cloud cover, much of the upward directed light from the fireball gets reflected back to earth by the cloud cover. This results in fire ignitions at greater ranges from the ground zero point.

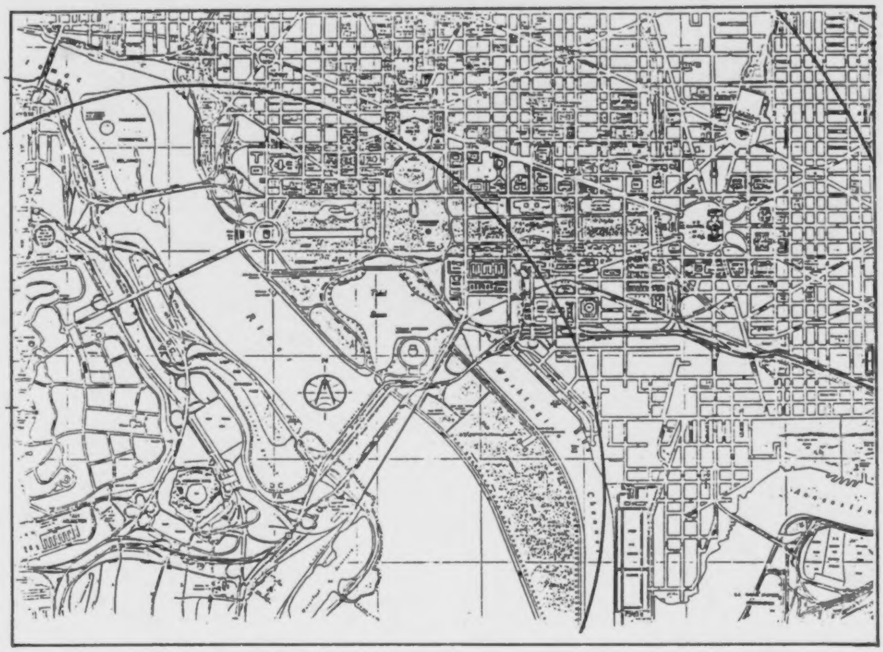

Figure 8.

A further increase in the range at which mass fires might be ignited is shown for the circumstance in which both cloud cover and snow cover are present. In this circumstance, much of the heat from the fireball is not absorbed by the ground, but is reflected back toward the sky and to surrounding objects. The heat refected into the sky gets re-reflected back to earth by the cloud cover, resulting in fire ignitions at still greater ranges from the detonation point.

Since most of the Soviet Union has extensive cloud and snow cover during long periods of winter months, this could be a source of a "nuclear winter" assymmetry of the type mentioned on page 6 of the written testimony.

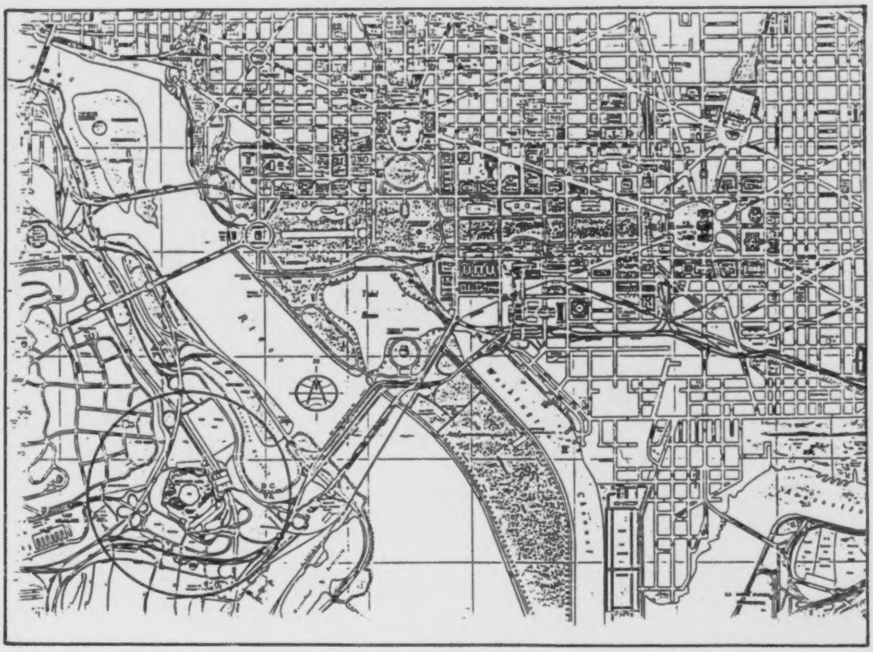

Figure 9.

The region subject to both a blast wave of about 5 pounds per square inch and 10 calories per square centimeter thermal radiation is shown for a 2 kiloton air burst. The area subject to an immediate fire and blast hazard would be about one square mile. Also worthy of note is that early fallout of the type described in figures 2 through 5 would not be present.

If a one kiloton earth penetrating warhead is used instead, the 5 pound per square inch blast range would be reduced by about a factor of two and the thermal ignition effects from the fireball would be reduced to several hundred feet. However, fires would be highly likely out to at least the 5 pound per square inch point because of ignitions induced by the passage of the shock wave.

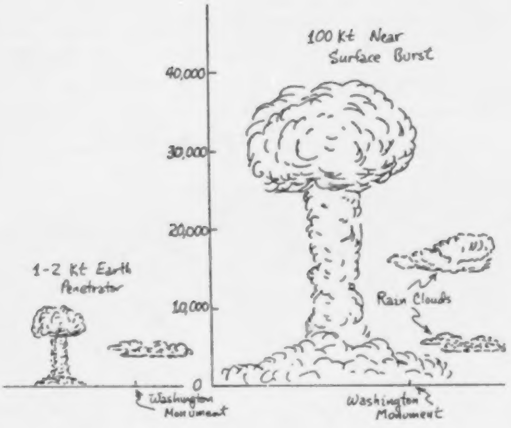
100 Kt Near
Surface Burst
40,000
30,000
20,000
10,000
0
1-2 Kt Earth
Penetrator
Rain Clouds
Washington
Monument
Washington
Monument

Figure 10.

The debris cloud from the one kiloton earth penetrator weapon would only rise to about 10,000 feet. It would therefore not inject debris into the stratosphere, but would, of course, leave these materials in the troposphere.

Since the penetrator detonates underground, the radioactive bomb materials condense onto particles which are large relative to those carried aloft by the near surface burst discussed in figures 2 through 5. These large particles fall from the debris cloud rapidly, mostly being deposited near the target area and immediately downwind. While they represent a very serious threat to those in the target area, they do not represent a significant threat to a distant attacker.

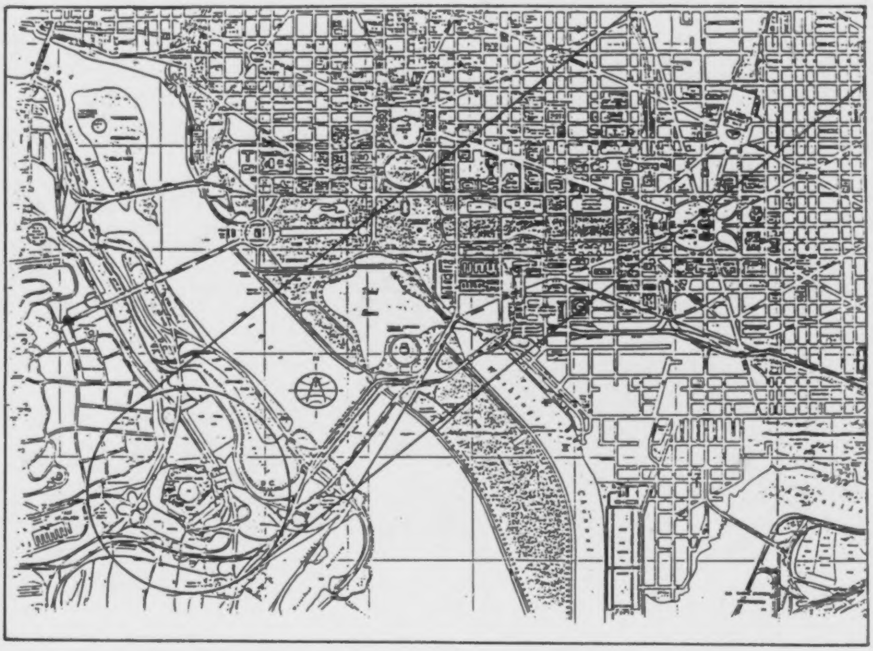

Figure 11.

The approximate downwind area that could be subject to severe fallout from a one kiloton earth penetrator attack is shown above. This fallout, while very intense, would mostly be confined to an area within 5 to 10 miles downwind of the target. See figures 2 throuh 5 and 9 and 10 for an explanation of the fallout phenomenon.

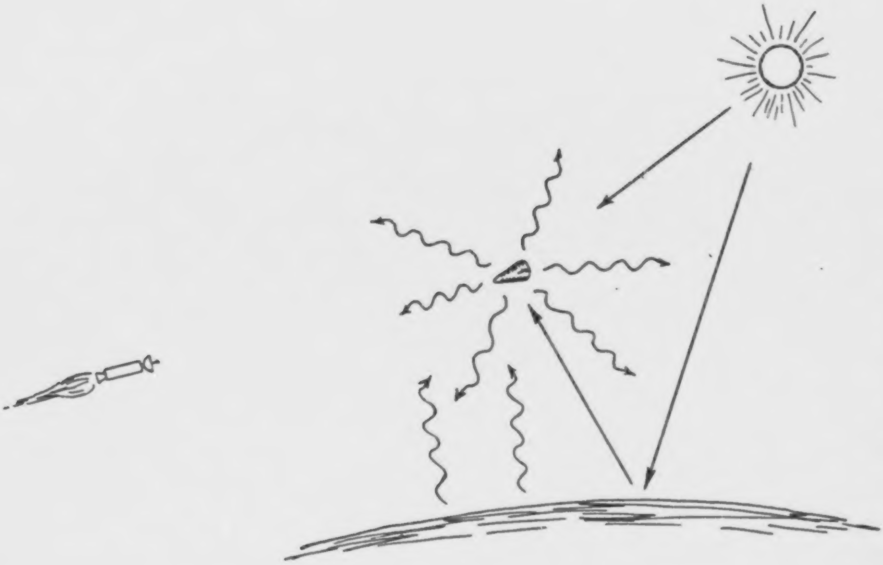

Figure 12.

The figure above, and the two to follow, illustrates a circumstance where a nuclear winter effect could have an adverse impact on the performance of a postulated defensive system.

Certain advanced defense concepts that are currently under study look for the long wavelength infrared radiation (LWIR) from threatening objects which are to be defended against. Since room temperature objects "glow" in the LWIR, they do not have to be illuminated by the sensor. LWIR sensors are compact and light, and do not require very large power supplies, as would a high powered radar. Therefore they are more easily flown on interceptors or mounted on satellites.

However, the LWIR signal from an object in space is a complicated mixture of "glow" from the room temperature object, LWIR reflected off the object from the sun, LWIR reflected from the sun to the surface of the earth and then onto the object, and LWIR "earth-shine" from the room temperature surface of the earth. See figure 13 next.

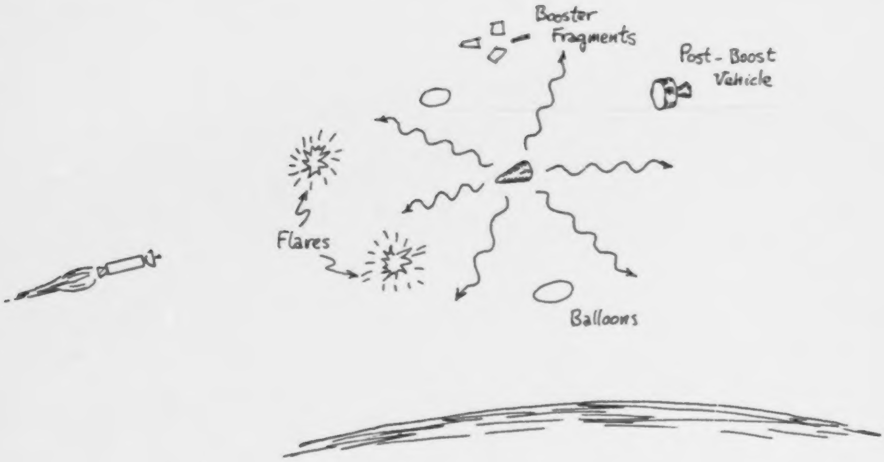

Figure 13.

A serious and perhaps unsolvable problem associated with these sensors is their inability to "discriminate" threatening objects (like attacking warheads) from other room temperature objects (like decoys) that also radiate LWIR. The sensor would try to accomplish this most difficult task by trying to observe small differences in intensity, wavelength, and object motion. Presumably, an adversary would try to counter this by heating some objects, cooling others, painting still others, flying flares and balloons, and the like, presenting a most challenging set of problems to the defense. See figure 14 next.

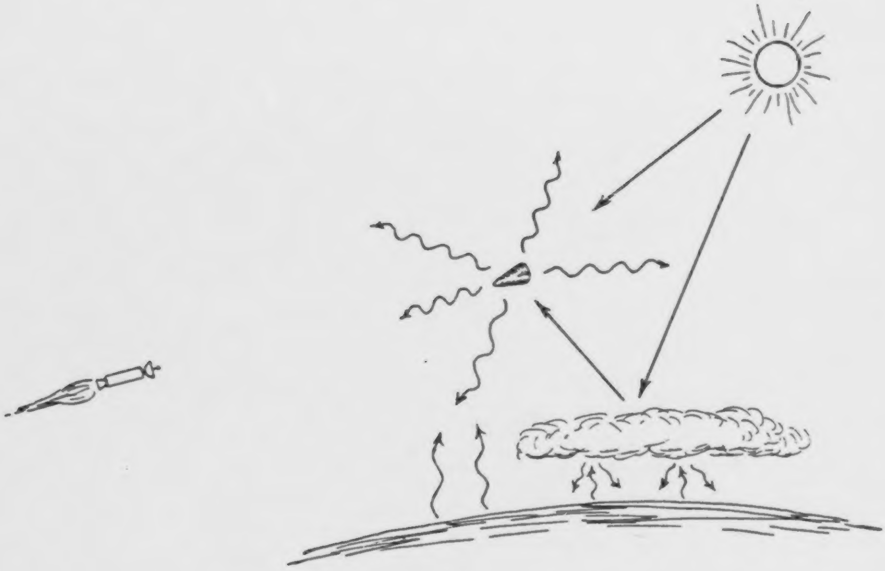

Figure 14.

In addition, the amount of earth-shine and reflected sunshine would not only vary with cloud cover, but will also vary with the altitude of injected smoke, the size of the smoke particles, their optical properties, as well as with the temperature of the upper atmosphere. Thus, adding to the problem of a hostile reacting adversary, the defensive system must have a very detailed and high quality understanding of the physical environment in which its sensors must operate.

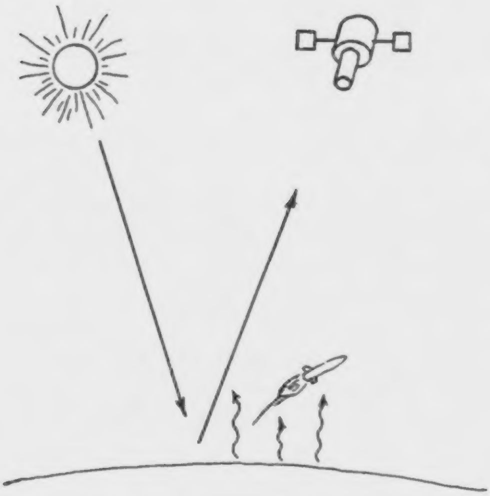

Figure 15.

As explained in the testimony, if the U.S. is to maintain an ability to control escalation in a limited nuclear war, it is vital that early warning and attack assessment systems provide leadership with timely, high quality and unambiguous information about possible enemy attacks.

A potentially valuable early warning system that could perform this task would be a satellite that could look for the short wave infrared radiation (SWIR) from the hot exhaust of a rocket's engines. However, this system would have to be able to observe the relatively dim signal from the rocket's exhaust against the very bright background of reflected light from the sun (see figure 16).

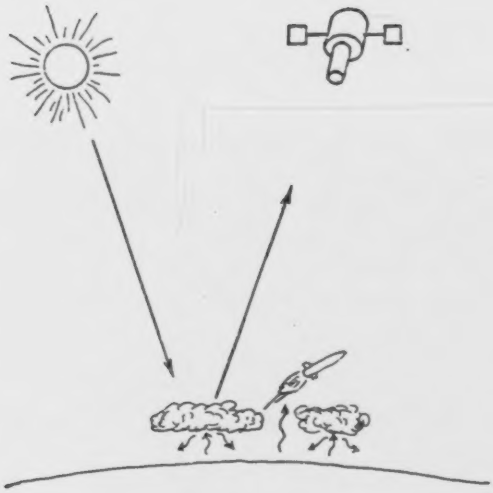

Figure 16.

A smoke filled atmosphere would both mask the earth's surface from, and reflect sunlight into, the sensors of the early warning system. In addition, changes in the upper atmosphere temperature could contribute a SWIR signal. The size, distribution and optical properties of the smoke could be important factors that determine whether or not such a system continues to function reliably.

Mr. **Scheuer**. Let me say that we must adjourn now. I must get over there. Your—both of your testimony will be reprinted in full in the record.

If you wish to add anything to your testimony based on what you may have heard here this morning, please feel free to do so and we will send you some additional questions by mail, which we will hold the record open for—give you an extra 10 or 12 days to get your answers back.

We deeply appreciate your patience and we apologize for having to curtail this hearing, but we're in a time bind and there's no alternative.

Thank you very much. We're very grateful to you both.

Dr. **Postol**. Thank you, Mr. Chairman.

[Whereupon, at 12:30 p.m., the subcommittee was adjourned, to reconvene subject to the call of the Chair.]

APPENDIX I

ADDITIONAL MATERIAL SUBMITTED FOR THE RECORD

THE AFTEREFFECTS OF NUCLEAR WAR

EDWARD TELLER

Introduction

In a serious and vital debate, it is most important to emphasize the points on which agreement exists as well as the limitations of these agreements. In discussing the present subject, one should state with all possible emphasis that the avoidance of nuclear war, indeed the avoidance of any serious war, may not be just the most important issue of our time, but is surpassed in importance by essentially none other. There are, however, widely varying and indeed mutually contradictory proposals concerning the way in which such wars may best be avoided. This statement is made to avoid misunderstandings concerning the spirit of the following arguments; in itself, it has limited bearing on the more technical issues that will follow.

The second point of basic agreement is that "nuclear winter" is an important topic. The possibility of widespread temperature changes following a nuclear attack should be clarified in every possible way, including the question of whether large-scale destructive effects are probable. There are some who claim that nuclear war will be probably followed by a nuclear winter. There are even those who assert that all scientists agree to the assertion that a dire nuclear winter would be a practically unavoidable consequence of a large-scale nuclear war. The following arguments will show in the first place that the uncertainties connected with nuclear winter are exceedingly great. The same arguments will also indicate that the nuclear winter recently sketched in the mass media is improbable.

History

Dangerous consequences of a nuclear war affecting non-combatants or even the whole human race have received a lot of attention. In the presidential campaign of 1956, Adlai Stevenson raised the problem of world-wide fallout in a manner that caught everyone's notice. The novel of Nevil Shute and its presentation as a film entitled "On The Beach" enhanced and perpetuated the belief that, due to effects of fallout, everyone would be endangered and quite possibly the human race would not survive. In the following years, the estimates of fallout were made more realistic and in the process were greatly reduced. Actually, in 1975, the National Academy of Sciences issued a report in which figures were given for the fallout so low as to have quite insignificant biological consequences. It later turned out that this report was in turn unrealistic. The National Academy of Sciences study had actually neglected several facts which would give rise to greater world-wide radiation doses due to fallout.[1]

At present it is estimated, on the basis of detailed calculations carried out in Livermore, that for non-belligerent countries in the Northern Hemisphere the fallout will expose people to an average dose of 20 rem (delivered in an external dose over 50 years, assuming no sheltering or weathering of the initial fallout patterns). Such irradiation is likely to produce some biological damage, but the level may be lower than what is statistically noticeable.

The figure of 20 rem holds on the average. Vagaries of the weather, particularly of the rainfall, can concentrate fallout in "hot spots" and give 50 year dose values in non-belligerent countries as high as 250 rems in limited areas. There is also some danger that radioactive elements may enter the food chains. People should be instructed as to the precautions to take against this. These precautions are quite simple and general knowledge on this subject should be much more widespread.[2] A given radiation dose received over a long period is generally less harmful than the same radiation dose received in a short time. The difference between the effects of doses delivered rapidly and slowly may be quite considerable, but there is much uncertainty as to how large this reduction in biological effect by slow delivery of the radiation dose may be.[3] The formula in current use accounting for the effect of continuing biological repair indicates that a dose as high as 250 rems would be nonfatal for almost the entire population. The damage to the human population worldwide due to fallout will be incomparably smaller than that which occurs in the combatant countries due to immediate effects of nuclear war.

The worst case of fallout occurs when all nuclear reactors and used fuel elements from nuclear reactors are subjected to explosions violent enough to disperse their radioactive contents. This effect is due to the circumstance that nuclear reactors produce on the average longer-lived radioactivity than do nuclear explosions. Under these conditions, the 20 rem average dose and the 250 rem "hot spot" dose given above may have to be multiplied by a factor of the order of eight, and fallout in the Northern Hemisphere outside the belligerent countries could then be quite large. However, this postulated dispersion of reactor radioactivity is not easy to accomplish nor does it appear to serve any military purpose. It is therefore unlikely to occur. Early underground disposal of wastes would greatly diminish this danger.

For all these reasons the final conclusion appears to be that, outside the belligerent countries, there is a small probability that fallout should play a major role.[4] Even in the belligerent countries, fallout will have less important effects by comparison to fire and destruction by blast, as long as elementary civil defense measures are exercised.[5]

The second major debate about worldwide consequences of a nuclear conflict occurred in the 1970's. Large nuclear explosions will loft fireball contents, including the molecule NO and its derivitives (NO_x), into the stratosphere. Those molecules are reactive and give rise to a number of chemical products which can stay in the stratosphere for a long time and deplete the ozone there. The ozone molecule is steadily regenerated by the solar radiation, but the presence of the NO_x residue from large nuclear explosions can keep the effective thickness of the ozone layer for a period of a year or two at levels possibly 30-40% below that of pre-war levels, with complete recovery taking several more years. (For purposes of comparison, the effective thickness of the ozone layer in the summertime is about 20% less over Seattle than it is over Miami.)

Ozone, even though present in small amounts, plays an important role as a shield against shortwave ultraviolet radiation. The calculated diminution of the ozone layer would give rise over the very long term to some increased incidence of skin cancer and, over the short term, to much faster development of sunburns that can be painful. These primary effects of the ozone depletion are non-trivial but not serious. Countermeasures against them and against any possible eye damage are easily taken if people are warned. A secondary argument has been made that ozone depletion and consequent increase in ultraviolet radiation can destroy some ultraviolet-sensitive plant or plankton species which in turn might have an important influence on the environment. Early springtime growths on plants also seem to be sensitive to ultraviolet radiation. Natural observed variations of ozone concentration with time and with geographical locations are comparable to the predicted effects following a nuclear war. Therefore, the total impact of ozone depletion is not apt to be very significant.

At this time the United States' arsenal has relatively few nuclear explosives with high enough yield to make great contributions to the depletion of the ozone layer. The reason is that smaller and more accurately aimed explosives appear to be militarily more effective. Lower yield weapons do not raise the fireball-borne NO_x to altitudes as high as larger ones and thus do far less damage to the ozone layer. The same trend has been adopted with some delay by the Soviet Union. Thus, the prospects for ozone depletion are declining for reasons that have nothing to do with the danger itself.

Calculational estimates of the ozone depletion following a nuclear exchange were first performed in 1974 at the Lawrence Livermore National Laboratory[6] and have been updated periodically since then.

Thus, two world-wide nuclear war effects, fallout and ozone depletion, initially heralded as indicating the end of the world, are now considered far less dangerous than at the times of peak concern regarding them.[7]

Approximately two years ago a third consequence of nuclear war started to occupy the limelight. This is the influence of the non-radioactive materials distributed in the atmosphere by the nuclear explosion upon the climate. This influence is due to a lesser degree to dust, to a greater degree to smoke. Both tend to reduce solar radiation received on the surface of the earth; if this reduction is sufficiently large and prolonged, it may bring about what is now known as "nuclear winter".

Of the two effects, the stirring up of dust has been discussed for a longer period and indeed some computer-based research on this topic has been carried out at the Lawrence Livermore National Laboratory.[8] There is an historical parallel to this effect in volcanic eruptions. In the tree rings of bristlecone pines, in which geological records of colder periods can be found for the last few thousand years, a correlation has been established with volcanic eruptions.[9] These events distributed dust in the atmosphere and created situations analogous to the raising of dust by nuclear explosions. In the case of historic volcanic events like the particularly big explosion of Santorini over three millenia ago in the Mediterranean and the smaller but very much better described eruption of Krakatoa in the Sunda Strait late in the last century, we have some measure of the lowering of world-wide temperature and, therefore, we have a handle on the relation between the observations on bristlecone pines and the world-wide temperature.

Using all these data, one comes to the conclusion that the raising of dust in a large-scale nuclear war, which probably is less than what occurs in the largest historic volcanic eruptions, involves atmospheric effects which will be noticeable but by no means severe. Better estimates of the mass of small dust particles lofted into the stratosphere will be difficult to develop, except perhaps by analysis of old air filter samples and from recent tests involving large amounts of high explosives.

In 1982 Crutzen and Birks[10] proposed that a much more serious effect on the atmosphere could be caused by the smoke from forest fires which not only scatter sunlight but actually significantly absorb it. In 1983 Turco, et. al[11] (TTAPS) argued that smoke generated in fires from bombed cities and possibly oil refineries would give even greater effects. Based on this paper, Dr. Carl Sagan has stated on numerous occasions that, following even a relatively small exchange of nuclear weapons, temperatures between latitudes 30 and 70 of the Northern Hemisphere would drop to values near 40 degrees Fahrenheit below the freezing point, causing great damage to all life and subsequent crop failures that would have further disasterous effects. He also argued that the smoke may well become distributed over the whole globe and that the survival of many species, including our own, would be endangered. While it is generally recognized that details of the process are still uncertain and deserve much more study, Dr. Sagan nevertheless has taken the position that the whole scenario is so robust that there can be little doubt about its main conclusions.

Therefore we have now reached, for a third time, a point where the introduction of a new world-wide consequence of nuclear war is currently believed by many to lead to deleterious effects even greater than the indubitable horrors likely to fall upon the combatant nations.

Uncertainties Concerning the Nuclear Winter

The danger of a nuclear winter differs from fallout and ozone depletion in an essential way. The nuclear winter depends on meteorological phenomena that involve much more detailed considerations and calculations than either the questions of fallout or ozone depletion, even though the latter requires the understanding of a complicated sequence of more than a hundred chemical reactions in the atmosphere. Therefore, to obtain reliable answers on temperature changes in the atmosphere in the case of the nuclear winter scenario will take a longer time and require more expenditure of thought and dollars than the elucidation of the other two dangers that have been noted.

This complicating factor does not in itself exclude the statement that the effect of smoke on world-wide temperatures may be robust and that the actual occurrence and the intensity of a nuclear winter could be predicted with confidence. However, detailed considerations of all processes, together with the uncertainties connected with them, lead to the conclusion, as will be shown below, that the argument for the occurrence of a nuclear winter, instead of being robust, is indeed quite inconclusive.

Since water is the agent which is largely responsible for the cleansing of the atmosphere of the smoke, we first make a comparison between the weight of the smoke to be expected from a nuclear attack and the weight of water (in the form of droplets and vapor) over the region between latitudes 30 and 70 in the Northern Hemisphere. Taking the estimate by Turco, et al. of 225 million tons of smoke (or 2.25×10^{14} grams) for their 5000 MT "baseline war" study, a simple calculation shows that this amount of smoke is still less than the weight of water in the same air mass by approximately a factor of ten thousand. This ratio of ten thousand-fold is useful as a guideline. However, in order to determine how long the smoke remains aloft, it is necessary to consider in what specific ways the smoke may be removed from the atmosphere. The average lifetime of a water molecule in the atmosphere is a little more than one week. So in ten days, before widespread smoke-associated cooling effect is established, a few thousand times greater mass of water will rain out than the total mass of the war-engendered smoke. How much smoke will remain aloft after this two weeks of rainout? This highly relevant question appears to be wide open.

A second fundamental reason why the prediction of a nuclear winter cannot be said to be robust is the great uncertainty in the quantity of smoke produced by the fires. A diminution of the smoke by a factor 5 below the Turco, et. al estimate will permit enough sunlight to penetrate down to the earth's surface to reduce the magnitude of the possible temperature change to barely discernable levels. If the smoke is reduced by a factor 10, the designation "nuclear winter" for the ensuing situation will become quite inappropriate.

In a systematic discussion of known and obvious uncertainties, we note that the amount of smoke which Turco, et al. estimate for their baseline case is about 225 million tons. In a recent detailed study[12] based on experience with forest fires and taking into account proper modifications when discussing the burning of all the cities that Turco's study has envisaged, it was proposed that the upper limit of smoke that might be emitted is 360 million tons while the lower limit is 15 million tons. These limits are not rigorous; somewhat higher and somewhat lower figures are possible. It is seen that the figure assumed by Turco, et al. is significantly closer to the upper limit than to the lower limit. Assuming the lower limit, the smoke would be reduced by a factor of 15 and that alone would suffice to allow more than 50-60% of the direct sunlight to come through. The net effect of the absorbed and scattered light would still not be negligible, but would certainly not result in anything like a nuclear winter. Early rainout of smoke would, of course, have similar consequences to reducing the extent or the smoke generation by the war-started fires.

In all these estimates, the amount of smoke generated (since urban fires burn principally wood) is proportional to the ratio of the weight of smoke emitted to the weight of wood burned. This ratio depends on many factors including moisture content and the manner of packing of wood, and more generally on the access of oxygen to the wood. In practical terms, the latter factors depend on the wind and on the size of the burning material. The temperature of the air reaching the burning process is also of importance; a higher temperature gives rise to a more complete burning. If we also consider the uncertainty in the areas of cities that will be ignited in an attack and, in addition, the uncertainty in the urban fuel densities contributing to the fires, we see that a detailed calculation may produce a quantity of smoke 10 times higher or 10 times lower than the nominal estimates.[12] Again, the Turco, et. al study used estimates near the upper end of the possible range of smoke generation values.

A point to be remembered in all these discussions is that the amount of wood in forests is usually considered to vary between 0.5 and 10 kilograms/m^2, while in cities the corresponding values are between 20 and perhaps 200 kilograms/m^2. It is of interest that the density of combustible materials in cities is generally greater than in forests. One consequence is that a fire storm, a relatively rare phenomenon in which practically all available oxygen is consumed, is essentially confined to the burning of the most densely fuel-laden cities.

The general conclusions appear to be that the burning of cities would contribute considerably more to world-wide smoke generation than would forest fires. The smoke generated by burning petroleum products in city fires tends to absorb light more strongly while the whiter smoke from burning wood contributes more to light scattering (the scattered light still has a chance to reach the earth's surface). The strength of light absorption of city smoke is a further uncertainty which influences possible temperature changes.

A further source of smoke will quite possibly be burning petroleum refineries. The fuel consumed in this process could approach 100 million tons or 10^{14} grams, of the same order as obtained from the other sources, though considerably lower than assumed by Turco, et al. However, the smoke particles from such fires would have a considerably higher light absorption and the temperature effect of the refinery fires could be comparable to the effect of burning cities.

In this short discussion, we have not mentioned the exceedingly great uncertainties due to our lack of knowledge of how the war would be conducted. If only military targets were attacked (and in some wars refineries may not count as military targets), the amount of smoke generated might be much lower than Dr. Sagan publicly asserts, and his argument for a nuclear winter would lose all of its force. An attacker may also not strike refineries in order to suppress smoke generation.

Thus the amount of smoke, upon which hypothesized temperature reductions depend in a sensitive manner, remains quite uncertain. We don't know how much smoke of what kind will be generated; we don't know how much will rain out before any remainder may become effective in reducing global temperature. The associated uncertainties in our knowledge on each of these points are not small ones.

We shall now turn to the great meteorological uncertainties. One interesting observation by Professor Lawrence Radke concerns the capping clouds that regularly develop in the smoke plumes above big fires. These clouds are due to condensed moisture which form droplets not big enough to develop into a rain. In one observation carried out six years ago, indications were found that most of the emitted smoke traversed the capping cloud; this natural smoke scrubber reduced the number of small smoke particles (between one-tenth and one-half micron in size), by a factor of 10. It is believed that this effect is due to the trapping of many small smoke particles in each of the water droplets and, that upon subsequent evaporation of the water droplets, these particles are then agglomerated into big units which are removed from the atmosphere more easily. These small particles are the most effective in preventing the sunlight from reaching the ground. The experiment was most unfortunately not repeated for lack of funds, although more such experiments are now being planned, stimulated by nuclear winter research.

A somewhat similar effect was observed by Hanel[13] who showed that smoke particles condense into bigger units if they are exposed to air in which the relative humidity exceeds 90%. Formation of bigger particles is of great importance because they are more easily removed from the air, by either wet or dry deposition processes, relative to smaller particles, and also because their influence on reducing sunlight at ground level is less per unit mass.

Let us now turn to the argument of Dr. Sagan which is adduced to prove that nuclear winter is practically unavoidable. This argument is that the smoke-loaded air, being heated by the sunlight, will attain sufficient buoyancy to rise toward the tropopause where the normal temperature of air is in the neighborhood of minus 50 to 60 °C. The presence of this smoke would make itself felt over broad areas for about one month and the temperature of the air in this region would be raised in a remarkable and understandable manner to about plus 5 °C while the surface temperature would be rapidly dropping. Thus, instead of the usual decrease of air temperature with increasing altitude, we would have an increasing temperature with altitude over the earth's land masses, called in meteorology an inversion. In such regions of inversion, the buoyancy mechanism that acts on rising air masses does not occur and water condensation and rain does not develop. Thus, Dr. Sagan infers that the smoke would persist in the upper atmosphere and, in spite of the presence of much more water vapor, shielding of the earth's surface from the sunlight could persist over long periods of time.

Actually, this mechanism for cooling of the earth's surface is effective only over land, while over the oceans where warm water is continually supplied from below for periods of many months, the temperature at the surface would remain essentially unchanged. Thus, over the surface of the earth unusually great temperature differences would be established between continents and oceans if a nuclear winter were ever to commence. These would probably result in violent air motions, widespread turbulence, and large, continuing rain storms, points mentioned even by Dr. Sagan and his colleagues (though not taken into account at all in their calculations).

There is reason to believe that the warm wet air over the oceans will rise only to a fraction of the altitude of the postulated smoke layer over the land areas. The primary cause of the storms is, therefore, concentrated in the lower part of the atmosphere. However, it is well known that storms and the associated turbulent air motion quite often extend far above the region of the original cause of the storm. Thus, water may be convected into the smoke-laden air layer over the continental margins, rain out the smoke, and thus prevent uniform distribution or long-term persistence of the smoke. One should also note that rain removing smoke from extensive areas while leaving it relatively untouched in other areas would give the smoke layer a patchy nature. This in turn would bring about additional large temperature differences which will further drive the atmospheric processes that will rain out the smoke. Rain out of large smoke layers may thereby proceed in an accelerating fashion.

A possibly more imporant doubt arises from the consideration that, according to every detailed calculation, the world-wide mixing and lofting of the smoke and the onset of nuclear winter takes about two weeks to develop. During this period, as noted above, most—perhaps virtually all—of the smoke is apt to be caught at lower altitudes and rained out there. By ignoring these several basic points, one might be led to the belief that one's argument for nuclear winter driven by persistent smoke is robust.

Initially, some smoke, particularly the strongly absorbing carbon particles resulting from oil fires, may be water-repellant. This property, however, changes after an exposure to air. Wood fires, moreover, appear to produce water-attracting particles even initially. Therefore, there is no reason to expect that rainout of all types of smoke particles would not occur.

We know that the average residence time of water vapor in the atmosphere is about a week. For particles, for instance the fine dust containing radioactivity after a nuclear explosion on the earth's surface, the removal time from the atmosphere varies between one and three weeks. There is no obvious reason why smoke, once water contacts it, should have a longer residence time. Indeed, relatively short atmospheric residence times of a week or less are what are expected on the basis of studies of the ongoing discharge rates of smoke into the atmosphere due to normal human and natural activities and observations of the average amount of smoke found in the atmosphere. The results of nuclear winter calculations will, therefore, be strongly affected if one neglects processes going on during the time needed for spreading the smoke world-wide and into the upper atmosphere.

These last points become, of course, less germane if the smoke is rapidly ejected to altitudes where contact with water vapor is less likely. Whether this actually would occur to a significant extent is quite unknown, but adds yet another dimension to the questions as to whether a nuclear winter could ever commence.

It is not contended that the arguments given above disprove the possibility of a nuclear winter. It is believed, however, that the reasons for very significant uncertainty are considerable in number and in weight. In particular, the best calculation carried out so far, by workers at the National Center for Atmospheric Research,[14] uses a somewhat more realistic model of the atmosphere which takes into account some of the basic geographical effects ignored by Turco, et. al (e.g., it has winds and oceans modelled). However, it still postulates that the injected smoke layer appears instantaneously everywhere and is held fixed in position and concentration in a uniform latitude band in the Northern Hemisphere, even while the violent abnormal convective processes created by the presence of this layer churn the entire upper atmosphere. Thus, in regard to the most crucial questions of rainout, transport and patchiness of smoke, this best-yet calculation does not even begin to provide estimates that can be considered seriously.

Considering all the uncertainties enumerated, it seems that the arguments for a nuclear winter would be more justly described not as "robust" but rather as "quite dubious".

Countermeasures

Since the possibility of a nuclear winter has not been conclusively excluded, the question arises what should be done about it. The first and most obvious measure is increased research which will help to decide the question. More funds should be allocated for experiments like those of Radke, McMahon and Ryan.[15] As another example, it should be stated that the Lawrence Livermore National Laboratory, which has plenty of capability and experience in this field, is able to devote only $1.5 million per year to such work at the present time; a similar sum is spent by LLNL on relevant general meteorological problems. I estimate that $30 million is being spent annually on atmospheric modelling nationwide. Greater amounts of money, carefully spent, would accelerate resolution of the basic questions regarding nuclear winter, and would also have an important impact on our ability to predict weather. A national research plan in these directions is now being developed by the National Climate Program Office of NOAA.

Actually, work on climate modeling in Livermore goes back to the year 1959 when I managed to authorize a small sum for an outstanding man, Chuck Leith, to commence utilization of our exceptional computational capabilities for some of the earliest research on this subject anywhere. Livermore's results have not been negligible in connection with the numerical modelling of nuclear winter and related effects of large-scale nuclear war but, as mentioned above, they are still far from conclusive. It will probably be several years before they can become so, under the best of circumstances.

In addition to arguing for more knowledge, I agree with Dr. Sagan that serious thought should be given to the avoidance of nuclear winter, even though I firmly hope that any nuclear war can be avoided and even though I believe that the development of a nuclear winter is far from certain under any circumstances. In this connection, I would like to quote a most outstanding physicist, Freeman Dyson, who in the New Yorker[16] has recently given much serious thought to questions connected with nuclear war. While Dr. Sagan says that the possibility of a nuclear winter will be tested at most only once, Dyson takes a very different view. He says, "The effects of the first nuclear war might be severe enough not to exterminate mankind but to leave our species in some sense incurably insane. Hatred and suffering on an unparalleled scale might lock us into a cyclical pattern of war and rearmament and revenge which would in the end make our planet uninhabitable."

I believe that the most grim consequences of a nuclear war are, indeed, not the material damage and not even the enormous loss of human life, but the probable spiritual damage to the fabric of human civilization extending over the whole world. In this I thoroughly agree with Professor Dyson.

Remarkably enough, it is not too difficult to ameliorate, by timely measures, much of the suffering, in case a nuclear war should occur. In this connection, it should be recalled that in 1982 the Soviet Union spent $13 per capita on civil defense while the United States spent 70¢ per capita. A part of the needed civil defense is the building of shelters and, in case we should subsequently discover that the possibility of lower temperatures is to be taken seriously, the construction and equipment of shelters should be appropriately modified.

But there is an even more important point. If anything approaching a nuclear winter should occur, widespread crop failures might be the most severe reason for human suffering and death. Methods for preservation of appropriate foods should be developed and major food stocks should be established worldwide. This may not only help in the survival of our own people, but it might save many lives abroad. Indeed, doing so would be a step away from the "incurable insanity" that Professor Dyson has mentioned.

In his article in Foreign Affairs,[17] Dr. Sagan suggested reduction of nuclear weapons which in two decades or a little more might eliminate the danger of nuclear winter. We have tried, almost since the end of World War II, to obtain Russian agreement to nuclear arms control. I believe that the arguments for Soviet adherence to any arms control agreement are less than robust. I am also sure that countermeasures of which we ourselves are capable can be executed in a few years rather than the period of decades suggested by Dr. Sagan. These methods include active defense, civil defense and food storage.

If we can destroy incoming missiles before they can set our cities, refineries, or forests afire, not only will nuclear winter be eliminated or at least made far less likely, but we may have also saved our lives and our society. Such a defense is feasible through use of antiballistic missiles and possibly other methods. Indeed, the very possibility of effective strategic defense may serve as a powerful deterrent to nuclear war.

But the action which will have to be taken without the slightest doubt is accelerated research, not only to resolve the question of a nuclear winter, but to help in the much broader field of understanding and predicting weather and climate. Man-made modification of climate is a natural outcome of our progressing science; it already occurs in and around large cities to discernable extents. When this becomes a more pervasive reality, it may well produce positive results in a peaceful world. It also will produce, without any doubts, some conflicts. That at the present time such research is proceeding on an international basis makes it more likely that the increased understanding will help to avoid or peacefully resolve such conflicts.

Footnotes

1. Long Term Effects of Multiple Nuclear-Weapons Detonations, National Academy of Sciences, Washington, D.C., 1975. The fallout estimates were based on actual weapons tests. These tests avoided atmospheric conditions where rainfall was expected. They were not carried out in the middle latitudes, and there is considerable difference between the mix of yields of weapons tested and the mix of weapons that will probably be used in a nuclear conflict. Furthermore, few groundbursts were tested. The result of all the difference is that the radioactive materials produced by the tests had a larger residence time in the stratosphere. Thus, when they returned to earth, less radioactivity was left in them than would be present in a nuclear war.

2. It must be admitted that while such knowledge is taught in the schools of the USSR, it is, remarkably enough, not readily available in the United States. The much-needed spread of this information throughout the world is a formidable job.

3. For radiation doses of less than 100 rem administered over a short time period, Glasstone and Dolan (The Effects of Nuclear Weapons, Government Printing Office, 1977) state that "Disabling sickness does not occur and exposed individuals should be able to proceed with their usual duties." Radiation doses will be received from worldwide fallout at a slow rate. This will permit partial biological repairs while the radiation damage occurs. The U.S. Federal Emergency Management Agency bases its estimates on a figure of 90% of the total radiation dose as repairable at the rate of 2.5% per day. Therefore, the radiation effects on people will be several-fold less than if the dose were received instantaneously, with the largest effective dose reductions being the worldwide ones.

4. An exception should be made for countries close to the belligerents. It is to be noted that Switzerland and Sweden have taken remarkably effective protective measures and will probably not suffer discernably from fallout.

5. A.A. Broyles, "Nuclear Explosions", American Journal of Physics, V. 50, p 586, 1982.

6. J.S. Chang, W. H. Duewer, and D.J. Webbles, "The Atmospheric Nuclear Tests of the 1950's and 1960's: A Possible Test of Ozone Depletion Theories", Journal of Geophysical Research, Vol. 84, p 1755, 1975.

   M.C. MacCracken and J.S. Chang, "A Preliminary Study of the Potential Chemical and Climatic Effects of Atmospheric Nuclear Explosions," Lawrence Livermore National Laboratory Rept. UCRL-51653, 1975.

   F. M. Luther, "Nuclear War: Short Term Chemical and Radiative Effects of Stratospheric Injections", Lawrence Livermore National Laboratory Rept. UCRL-89957, presented at the Third International Conference on Nuclear War, Erice, Sicily, August 19-24, 1983.

   These calculations have recently been extended to determine the possibility that holes in the ozone layer may be created and last for a few days after the exchange. It is found that this is very unlikely to be a significant effect.

7. Jonathan Shell in The Fate of the Earth (Knopf, 1982) first reproduces the moderate conclusions of the National Academy of Sciences study (see Footnote 1) in a correct manner, but in successive repetitions of this situation, he increasingly exaggerates the effects. Without having introduced any new scientific evidence, he eventually suggests that life on earth may be wiped out as a result of the reduction of the ozone layer following nuclear war. The National Academy study implied no such result, and indeed the subsequent OTA study ("The Effects of Nuclear War", Congressional Office of Technology Assessment, 1979) concluded that altered understanding and circumstances since the NAS study "...cast doubt on the likelihood of serious ozone depletion as a consequence of nuclear war."

8. R.G. Gutmacher and G.H. Higgins, "Total Mass and Concentration of Particles in Dust Clouds," Lawrence Livermore National Laboratory Rept. UCRL-14397, September 1965.

9. V.C. LaMarche, Jr. and K.K. Hirschboeck, "Frost Rings in Trees as Records of Major Volcanic Eruptions," Nature, Vol. 307, p 121, 12 January 1984.

10. P.J. Crutzen and J.W. Birks, "The Atmosphere After a Nuclear War: Twilight at Noon," Ambio, Vol XI, p 115, 1982.

11. R.P. Turco, O.B. Toon, T.P. Ackerman, J.B. Pollack, and C. Sagan, "Global Atmospheric Consequences of Nuclear War", Science, Vol. 222, p 1283 (1983).

12. A.A. Broyles, "Smoke Generated in a Nuclear War," submitted to the American Journal of Physics. It is noted there that the thermal energy per unit area required to ignite an area, the fuel per unit area to be burned, and the weight of smoke produced per unit weight of fuel burned are factors required to calculate the quantity of smoke generated in a nuclear attack. According to Stan Martin and Associates (Attack Manual for Civil Defense Planners, Chapter 3, April 1983, Lawrence Livermore National Laboratory Rept. UCRL-15544), the energy required to ignite an area can be taken to be 25 calories per square centimeter. This number is uncertain to a factor of 2; that is, it may be too large by a factor of two or it may be one-half the correct number. According to results regarding the five cities studied for the Office of Civil Defense, 1970 (now FEMA, 500 C Street, Washington, D.C. 20472), the fuel density present in cities is 20 kilograms per square meter, again with an uncertainty of a factor of two. Since, according to the National Bureau of Standards Center for Fire Research surveys, the predominant fuel in cities is wood and paper products, we can take the data obtained in measurements made by forest researchers to indicate the weight of smoke emitted by the burning of a unit weight of wood. According to C.K. McMahon and P.W. Ryan, ("Some Chemical and Physical Characteristics of Emissions from Forest Fires", Southern Forest Fire Laboratory, Route 1, Box 182A, Dry Branch, GA 31020), this number is 0.01 with a variability of five-fold. Calculation of the amount of smoke generated by burning the wooden structures of cities using these numbers is then uncertain by 2 times 5, or 10. (The latter uncertainty is probably somewhat greater than 5, because the burning of wood in a large city fire will be under different conditions than those of an open forest fire. It would depend, for example, on the shapes and sizes of the structures burned.)

13. G. Hanel, "Influence of Relative Humidity on Aerosol Deposition by Sedimentation," *Atmos. Environment*, Vol. 16, No. 11, pp. 2703-2706, 1982.

14. C. Covey, S.H. Schneider, and S.L. Thompson, "Global Atmospheric Effects of Massive Smoke Injections from a Nuclear War: Results from General Circulation Model Simulation," *Nature*, *308*, 21-25.

15. L.F. Radke, J.H. Lyons, D.A. Hegg, and P.V. Hobbs, "Airborne Monitoring and Smoke Characterizations of Prescribed Fires on Forest Lands in Western Washington and Oregon", Final Report for Lockheed-EMSKO Project Numbers AM526 and AM680.

    C.K. McMahon and P.W. Ryan, U.S. Department of Agriculture Forest Service, Macon, Georgia, "Some Chemical and Physical Characteristics of Emissions from Forest Fires," presented at the 69th Annual Meeting of the Air Pollution Association, Portland, Oregon, June 27-July 1, 1976.

16. Freeman Dyson, *Weapons and Hope*, (Harper & Row), reprinted in *The New Yorker*, February 6, 13, 20, and 27, 1984, issues.

17. Carl Sagan, "Nuclear War and Climatic Catastrophe: Some Policy Implications," *Foreign Affairs*, Winter 1983/84, page 257.

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Carl Sagan

WINTER 1983/84 No. 62202

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NUCLEAR WAR AND CLIMATIC CATASTROPHE: SOME POLICY IMPLICATIONS

> It is not even impossible to imagine that the effects of an atomic war fought with greatly perfected weapons and pushed by the utmost determination will endanger the survival of man
>
> Edward Teller
> *Bulletin of the Atomic Scientists*, February 1947

> The extreme danger to mankind inherent in the proposal by [Edward Teller and others to develop thermonuclear weapons] wholly outweighs any military advantage.
>
> J. Robert Oppenheimer, *et al.*
> *Report of the General Advisory Committee, AEC*
> October 1949

> The fact that no limits exist to the destructiveness of this weapon makes its very existence and the knowledge of its construction a danger to humanity. . . . It is . . . an evil thing.
>
> Enrico Fermi and I. I. Rabi
> Addendum, *ibid.*

> A very large nuclear war would be a calamity of indescribable proportions and absolutely unpredictable consequences, with the uncertainties tending toward the worse. . . . All-out nuclear war would mean the destruction of contemporary civilization, throw man back centuries, cause the deaths of hundreds of millions or billions of people, and, with a certain degree of probability, would cause man to be destroyed as a biological species . . .
>
> Andrei Sakharov
> *Foreign Affairs*, Summer 1983

Apocalyptic predictions require, to be taken seriously, higher standards of evidence than do assertions on other matters

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Carl Sagan is David Duncan Professor of Astronomy and Space Sciences and Director of the Laboratory for Planetary Studies at Cornell University. He has played a leading role in the Mariner, Viking and Voyager expeditions to the planets, for which he has received the NASA medals for Exceptional Scientific Achievement and (twice) for Distinguished Public Service. Study of the Martian atmosphere led to the research by Dr. Sagan and his colleagues described here. He has served as Chairman of the Division for Planetary Sciences of the American Astronomical Society; as President of the Planetology Section of the American Geophysical Union; and, for 12 years, as Editor of *Icarus*, the leading professional journal in planetary science. Dr. Sagan is also a recipient of the Peabody Award and the Pulitzer Prize.

where the stakes are not as great. Since the immediate effects of even a single thermonuclear weapon explosion are so devastating, it is natural to assume—even without considering detailed mechanisms—that the more or less simultaneous explosion of ten thousand such weapons all over the Northern Hemisphere might have unpredictable and catastrophic consequences.

And yet, while it is widely accepted that a full nuclear war might mean the end of civilization at least in the Northern Hemisphere, claims that nuclear war might imply a reversion of the human population to prehistoric levels, or even the extinction of the human species, have, among some policymakers at least, been dismissed as alarmist or, worse, irrelevant. Popular works that stress this theme, such as Nevil Shute's *On the Beach,* and Jonathan Schell's *The Fate of the Earth,* have been labeled disreputable. The apocalyptic claims are rejected as unproved and unlikely, and it is judged unwise to frighten the public with doomsday talk when nuclear weapons are needed, we are told, to preserve the peace. But, as the above quotations illustrate, comparably dire warnings have been made by respectable scientists with diverse political inclinations, including many of the American and Soviet physicists who conceived, devised and constructed the world nuclear arsenals.

Part of the resistance to serious consideration of such apocalyptic pronouncements is their necessarily theoretical basis. Understanding the long-term consequences of nuclear war is not a problem amenable to experimental verification—at least not more than once. Another part of the resistance is psychological. Most people—recognizing nuclear war as a grave and terrifying prospect, and nuclear policy as immersed in technical complexities, official secrecy and bureaucratic inertia—tend to practice what psychiatrists call denial: putting the agonizing problem out of our heads, since there seems nothing we can do about it. Even policymakers must feel this temptation from time to time. But for policymakers there is another concern: if it turns out that nuclear war could end our civilization or our species, such a finding might be considered a retroactive rebuke to those responsible, actively or passively, in the past or in the present, for the global nuclear arms race.

The stakes are too high for us to permit any such factors to influence our assessment of the consequences of nuclear war. If nuclear war now seems significantly more catastrophic than has generally been believed in the military and policy communities, then serious consideration of the resulting implications is urgently called for.

It is in that spirit that this article seeks, first, to present a short summary, in lay terms, of the climatic and biological consequences of nuclear war that emerge from extensive scientific studies conducted over the past two years, the essential conclusions of which have now been endorsed by a large number of scientists. These findings were presented in detail at a special conference in Cambridge, Mass., involving almost 100 scientists on April 22–26, 1983, and were publicly announced at a conference in Washington, D.C., on October 31 and November 1, 1983. They have been reported in summary form in the press, and a detailed statement of the findings and their bases will be published in *Science*.[1] The present summary is designed particularly for the lay reader.

Following this summary, I explore the possible strategic and policy implications of the new findings.* They point to one apparently inescapable conclusion: the necessity of moving as rapidly as possible to reduce the global nuclear arsenals below levels that could conceivably cause the kind of climatic catastrophe and cascading biological devastation predicted by the new studies. Such a reduction would have to be to a small percentage of the present global strategic arsenals.

II

The central point of the new findings is that the long-term consequences of a nuclear war could constitute a global climatic catastrophe.

The immediate consequences of a single thermonuclear weapon explosion are well known and well documented—fireball radiation,

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[1] R. P. Turco, O. B. Toon, T. P. Ackerman, J. B. Pollack and Carl Sagan [TTAPS], "Global Atmospheric Consequences of Nuclear War," *Science*, in press; P. R. Ehrlich, M. A. Harwell, Peter H. Raven, Carl Sagan, G. M. Woodwell, *et al.*, "The Long-Term Biological Consequences of Nuclear War," *Science*, in press.

* For stimulating discussions, and/or careful reviews of an earlier version of this article, I am grateful to Hans Bethe, McGeorge Bundy, Joan Chittester, Freeman Dyson, Paul Ehrlich, Alton Frye, Richard Garwin, Noel Gayler, Jerome Grossman, Averell Harriman, Mark Harwell, John P. Holdren, Eric Jones, George F. Kennan, Robert S. McNamara, Carson Mark, Philip Morrison, Jay Orear, William Perry, David Pimentel, Theodore Postel, George Rathjens, Joseph Rotblat, Herbert Scoville, Brent Scowcroft, John Steinbruner, Jeremy Stone, Edward Teller, Brian Toon, Richard Turco, Paul Warnke, Victor Weisskopf, Robert R. Wilson, and Albert Wohlstetter. They are however in no way to be held responsible for the opinions stated or the conclusions drawn. I deeply appreciate the encouragement, suggestions and critical assessments provided by Lester Grinspoon, Steven Soter and, especially, Ann Druyan, and the dedicated transcriptions, through many drafts, by Mary Roth.

This article would not have been possible without the high scientific competence and dedication of my co-authors on the TTAPS study, Richard P. Turco, Owen B. Toon, Thomas P. Ackerman, and James B. Pollack, and my 19 coauthors of the accompanying scientific paper on the long-term biological consequences of nuclear war. Finally, I wish to thank my Soviet colleagues, V. V. Alexandrov, E. I. Chazov, G. S. Golitsyn, and E. P. Velikhov among others, for organizing independent confirmations of the probable existence of a post-nuclear-war climatic catastrophe, and for helping to generate a different kind of climate—one of mutual concern and cooperation that is essential if we are to emerge safely from the trap that our two nations have jointly set for ourselves, our civilization, and our species.

prompt neutrons and gamma rays, blast, and fires.[2] The Hiroshima bomb that killed between 100,000 and 200,000 people was a fission device of about 12 kilotons yield (the explosive equivalent of 12,000 tons of TNT). A modern thermonuclear warhead uses a device something like the Hiroshima bomb as the trigger—the "match" to light the fusion reaction. A typical thermonuclear weapon now has a yield of about 500 kilotons (or 0.5 megatons, a megaton being the explosive equivalent of a million tons of TNT). There are many weapons in the 9 to 20 megaton range in the strategic arsenals of the United States and the Soviet Union today. The highest-yield weapon ever exploded is 58 megatons.

Strategic nuclear weapons are those designed for delivery by ground-based or submarine-launched missiles, or by bombers, to targets in the adversary's homeland. Many weapons with yields roughly equal to that of the Hiroshima bomb are today assigned to "tactical" or "theater" military missions, or are designated "munitions" and relegated to ground-to-air and air-to-air missiles, torpedoes, depth charges and artillery. While strategic weapons often have higher yields than tactical weapons, this is not always the case.[3] Modern tactical or theater missiles (e.g., Pershing II, SS-20) and air support weapons (e.g., those carried by F-15 or MiG-23 aircraft) have sufficient range to make the distinction between "strategic" and "tactical" or "theater" weapons increasingly artificial. Both categories of weapons can be delivered by land-based missiles, sea-based missiles, and aircraft; and by intermediate-range as well as intercontinental delivery systems. Nevertheless, by the usual accounting, there are around 18,000 strategic thermonuclear weapons (warheads) and the equivalent number of fission triggers in the American and Soviet strategic arsenals, with an aggregate yield of about 10,000 megatons.

The total number of nuclear weapons (strategic plus theater and tactical) in the arsenals of the two nations is close to 50,000, with an aggregate yield near 15,000 megatons. For convenience, we here collapse the distinction between strategic and theater weapons, and adopt, under the rubric "strategic," an aggregate yield of 13,000 megatons. The nuclear weapons of the rest of the world—

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[2] Samuel Glasstone and Philip J. Dolan, *The Effects of Nuclear War*, 3rd ed., Washington: Department of Defense, 1977.

[3] The "tactical" Pershing I, for example, is listed as carrying warheads with yields as high as 400 kilotons, while the "strategic" Poseidon C-3 is listed with a yield of only 40 kilotons. *World Armaments and Disarmament, SIPRI Yearbook 1982*, Stockholm International Peace Research Institute, London: Taylor and Francis, 1982; J. Record, *U.S. Nuclear Weapons in Europe*, Washington: Brookings Institution, 1974.

mainly Britain, France and China—amount to many hundred warheads and a few hundred megatons of additional aggregate yield.

No one knows, of course, how many warheads with what aggregate yield would be detonated in a nuclear war. Because of attacks on strategic aircraft and missiles, and because of technological failures, it is clear that less than the entire world arsenal would be detonated. On the other hand, it is generally accepted, even among most military planners, that a "small" nuclear war would be almost impossible to contain before it escalated to include much of the world arsenals.[4] (Precipitating factors include command and control malfunctions, communications failures, the necessity for instantaneous decisions on the fates of millions, fear, panic and other aspects of real nuclear war fought by real people.) For this reason alone, any serious attempt to examine the possible consequences of nuclear war must place major emphasis on large-scale exchanges in the five-to-seven-thousand-megaton range, and many studies have done so.[5] Many of the effects described below, however, can be triggered by much smaller wars.

The adversary's strategic airfields, missile silos, naval bases, submarines at sea, weapons manufacturing and storage locales, civilian and military command and control centers, attack assessment and early warning facilities, and the like are probable targets ("counterforce attack"). While it is often stated that cities are not targeted "per se," many of the above targets are very near or colocated with cities, especially in Europe. In addition, there is an industrial targeting category ("countervalue attack"). Modern nuclear doctrines require that "war-supporting" facilities be attacked. Many of these facilities are necessarily industrial in nature and engage a work force of considerable size. They are almost always situated near major transportation centers, so that raw materials and finished products can be efficiently transported to other industrial sectors, or to forces in the field. Thus, such facilities are, almost by definition, cities, or near or within cities. Other "war-supporting" targets may include the transportation systems themselves (roads, canals, rivers, railways, civilian airfields, etc.), petroleum refineries, storage sites and pipelines, hydroelectric plants, radio and television transmitters and the like. A major countervalue attack therefore might involve almost all large cities in the United States and the Soviet Union, and possibly most of the large cities in the Northern Hemisphere.[6] There are fewer than 2,500 cities in the world with populations over 100,000 inhabitants, so the devastation of all such cities is well within the means of the world nuclear arsenals.

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[4] See, e.g., D. Ball, Adelphi Paper 169, London: International Institute for Strategic Studies, 1981; P. Bracken and M. Shubik, in *Technology in Society*, Vol. 4, 1982, p. 155.

[5] National Academy of Sciences/National Research Council, *Long-term Worldwide Effects of Multiple Nuclear Weapons Detonations*, Washington: National Academy of Sciences, 1975; Office of Technology Assessment, *The Effects of Nuclear War*, Washington, 1979; J. Peterson (Ed.), *Nuclear War: The Aftermath*, special issue *Ambio*, Vol. 11, Nos. 2–3, Royal Swedish Academy of Sciences, 1982; R. P. Turco, *et al., loc. cit.* footnote 1; S. Bergström, *et al., Effects of Nuclear War on Health and Health Services*, Rome: World Health Organization, Publication No. A36.12, 1983; National Academy of Sciences, new 1983 study in press.

Recent estimates of the immediate deaths from blast, prompt radiation, and fires in a major exchange in which cities were targeted range from several hundred million to 1.1 billion people—the latter estimate is in a World Health Organization study in which targets were assumed not to be restricted entirely to NATO and Warsaw Pact countries.[7] Serious injuries requiring immediate medical attention (which would be largely unavailable) would be suffered by a comparably large number of people, perhaps an additional 1.1 billion.[8] Thus it is possible that something approaching half the human population on the planet would be killed or seriously injured by the direct effects of the nuclear war. Social disruption; the unavailability of electricity, fuel, transportation, food deliveries, communications and other civil services; the absence of medical care; the decline in sanitation measures; rampant disease and severe psychiatric disorders would doubtless collectively claim a significant number of further victims. But a range of additional effects—some unexpected, some inadequately treated in earlier studies, some uncovered only recently—now make the picture much more somber still.

Because of current limitations on missile accuracy, the destruction of missile silos, command and control facilities, and other hardened sites requires nuclear weapons of fairly high yield exploded as groundbursts or as low airbursts. High-yield groundbursts will vaporize, melt and pulverize the surface at the target area and propel large quantities of condensates and fine dust into the upper troposphere and stratosphere. The particles are chiefly entrained in the rising fireball; some ride up the stem of the mushroom cloud. Most military targets, however, are not very hard. The destruction of cities can be accomplished, as demonstrated at Hiroshima and Nagasaki, by lower-yield explosions less than a kilometer above the surface. Low-yield airbursts over cities or near forests will tend to produce massive fires, some of them over areas of 100,000 square kilometers or more. City fires generate enormous quantities of black oily smoke which rise at least into the upper part of the lower

[6] See, e.g., J. Peterson, *op. cit.* footnote 5.

[7] S. Bergstrom, *op. cit.* footnote 5.

[8] *Ibid.*

atmosphere, or troposphere. If firestorms occur, the smoke column rises vigorously, like the draft in a fireplace, and may carry some of the soot into the lower part of the upper atmosphere, or stratosphere. The smoke from forest and grassland fires would initially be restricted to the lower troposphere.

The fission of the (generally plutonium) trigger in every thermonuclear weapon and the reactions in the (generally uranium-238) casing added as a fission yield "booster" produce a witch's brew of radioactive products, which are also entrained in the cloud. Each such product, or radioisotope, has a characteristic "half-life" (defined as the time to decay to half its original level of radioactivity). Most of the radioisotopes have very short half-lives and decay in hours to days. Particles injected into the stratosphere, mainly by high-yield explosions, fall out very slowly—characteristically in about a year, by which time most of the fission products, even when concentrated, will have decayed to much safer levels. Particles injected into the troposphere by low-yield explosions and fires fall out more rapidly—by gravitational settling, rainout, convection, and other processes—before the radioactivity has decayed to moderately safe levels. Thus rapid fallout of tropospheric radioactive debris tends to produce larger doses of ionizing radiation than does the slower fallout of radioactive particles from the stratosphere.

Nuclear explosions of more than one-megaton yield generate a radiant fireball that rises through the troposphere into the stratosphere. The fireballs from weapons with yields between 100 kilotons and one megaton will partially extend into the stratosphere. The high temperatures in the fireball chemically ignite some of the nitrogen in the air, producing oxides of nitrogen, which in turn chemically attack and destroy the gas ozone in the middle stratosphere. But ozone absorbs the biologically dangerous ultraviolet radiation from the Sun. Thus the partial depletion of the stratospheric ozone layer, or "ozonosphere," by high-yield nuclear explosions will increase the flux of solar ultraviolet radiation at the surface of the Earth (after the soot and dust have settled out). After a nuclear war in which thousands of high-yield weapons are detonated, the increase in biologically dangerous ultraviolet light might be several hundred percent. In the more dangerous shorter wavelengths, larger increases would occur. Nucleic acids and proteins, the fundamental molecules for life on Earth, are especially sensitive to ultraviolet radiation. Thus, an increase of the solar ultraviolet flux at the surface of the Earth is potentially dangerous for life.

These four effects—obscuring smoke in the troposphere, obscuring dust in the stratosphere, the fallout of radioactive debris, and the partial destruction of the ozone layer—constitute the four known principal adverse environmental consequences that occur after a nuclear war is "over." There may be others about which we are still ignorant. The dust and, especially, the dark soot absorb ordinary visible light from the Sun, heating the atmosphere and cooling the Earth's surface.

All four of these effects have been treated in our recent scientific investigation.[9] The study, known from the initials of its authors as TTAPS, for the first time demonstrates that severe and prolonged low temperatures would follow a nuclear war. (The study also explains the fact that no such climatic effects were detected after the detonation of hundreds of megatons during the period of U.S.-Soviet atmospheric testing of nuclear weapons, ended by treaty in 1963: the explosions were sequential over many years, not virtually simultaneous; and, occurring over scrub desert, coral atolls, tundra and wasteland, they set no fires.) The new results have been subjected to detailed scrutiny, and half a dozen confirmatory calculations have now been made. A special panel appointed by the National Academy of Sciences to examine this problem has come to similar conclusions.[10]

Unlike many previous studies, the effects do not seem to be restricted to northern mid-latitudes, where the nuclear exchange would mainly take place. There is now substantial evidence that the heating by sunlight of atmospheric dust and soot over northern mid-latitude targets would profoundly change the global circulation. Fine particles would be transported across the equator in weeks, bringing the cold and the dark to the Southern Hemisphere. (In addition, some studies suggest that over 100 megatons would be dedicated to equatorial and Southern Hemisphere targets, thus generating fine particles locally.)[11] While it would be less cold and less dark at the ground in the Southern Hemisphere than in the Northern, massive climatic and environmental disruptions may be triggered there as well.

In our studies, several dozen different scenarios were chosen, covering a wide range of possible wars, and the range of uncertainty in each key parameter was considered (e.g., to describe how many fine particles are injected into the atmosphere). Five representative cases are shown in Table 1, below, ranging from a small low-yield attack exclusively on cities, utilizing, in yield, only 0.8 percent of the world strategic arsenals, to a massive exchange involving 75

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[9] R. P. Turco, *et al.*, *loc. cit.* footnote 1.

[10] National Academy of Sciences, 1983, *loc. cit.* footnote 5.

[11] J. Peterson, *op. cit.* footnote 6.

TABLE 1
NUCLEAR EXCHANGE SCENARIOS

Case	Total Yield (MT)	% Yield Surface Bursts	% Yield Urban or Industrial Targets	Warhead Yield Range (MT)	Total Number of Explosions
1. Baseline Case, countervalue and counterforce[a]	5,000	57	20	0.1–10	10,400
11. 3,000 MT nominal, counterforce only[b]	3,000	50	0	1 –10	2,250
14. 100 MT nominal, countervalue only[c]	100	0	100	0.1	1,000
16. 5000 MT "severe," counterforce only[b,d]	5,000	100	0	5 –10	700
17. 10,000 MT "severe," countervalue and counterforce[c,d]	10,000	63	15	0.1–10	16,160

a. In the Baseline Case, 12,000 square kilometers of inner cities are burned; on every square centimeter an average of 10 grams of combustibles are burned, and 1.1% of the burned material rises as smoke. Also, 230,000 square kilometers of suburban areas burn, with 1.5 grams consumed at each square centimeter and 3.6% rising as smoke.

b. In this highly conservative case, it is assumed that no smoke emission occurs, that not a blade of grass is burned. Only 25,000 tons of the fine dust is raised into the upper atmosphere for every megaton exploded.

c. In contrast to the Baseline Case, only inner cities burn, but with 10 grams per square centimeter consumed and 3.3% rising as smoke into the high atmosphere.

d. Here, the fine (submicron) dust raised into the upper atmosphere is 150,000 tons per megaton exploded.

percent of the world arsenals. "Nominal" cases assume the most probable parameter choices; "severe" cases assume more adverse parameter choices, but still in the plausible range.

Predicted continental temperatures in the Northern Hemisphere vary after the nuclear war according to the curves shown in Figure 1 on the following page. The high heat-retention capacity of water guarantees that oceanic temperatures will fall at most by a few degrees. Because temperatures are moderated by the adjacent oceans, temperature effects in coastal regions will be less extreme than in continental interiors. The temperatures shown in Figure 1 are average values for Northern Hemisphere land areas.

Even much smaller temperature declines are known to have serious consequences. The explosion of the Tambora volcano in Indonesia in 1815 led to an average global temperature decline of only 1°C, due to the obscuration of sunlight by the fine dust propelled into the stratosphere; yet the hard freezes the following year were so severe that 1816 has been known in Europe and America as "the year without a summer." A 1°C cooling would

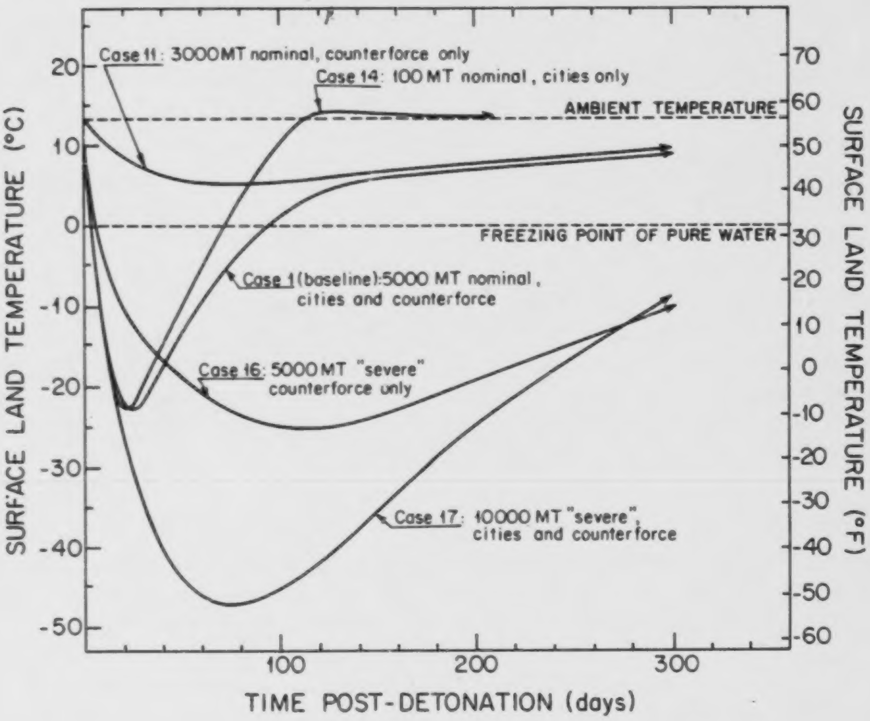

FIGURE 1

TEMPERATURE EFFECTS OF NUCLEAR WAR CASES

NOTE: In this Figure, the average temperature of Northern Hemisphere land areas (away from coastlines) is shown varying with time after the five Cases of nuclear war defined in Table 1. The "ambient" temperature is the average in the Northern Hemisphere over all latitudes and seasons: thus, normal winter temperatures at north temperature latitudes are lower than is shown, and normal tropical temperatures are higher than shown. Cases described as "nominal" assume the most likely values of parameters (such as dust particle size or the frequency of firestorms) that are imperfectly known. Cases marked "severe" represent adverse but not implausible values of these parameters. In Case 14 the curve ends when the temperatures come within a degree of the ambient values. For the four other Cases the curves are shown ending after 300 days, but this is simply because the calculations were not extended further. In these four Cases the curves will continue to the directions they are headed.

nearly eliminate wheat growing in Canada.[12] In the last thousand years, the maximum global or Northern Hemisphere temperature deviations have been around 1°C. In an Ice Age, a typical long-term temperature decline from preexisting conditions is about 10°C. Even the most modest of the cases illustrated in Figure 1 give temporary temperature declines of this order. The Baseline Case is much more adverse. Unlike the situation in an Ice Age, however, the global temperatures after nuclear war plunge rapidly and take only months to a few years to recover, rather than thousands of years. No new Ice Age is likely to be induced by a Nuclear Winter.

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[12] National Academy of Sciences, 1975, *op. cit.* footnote 5.

Because of the obscuration of the Sun, the daytime light levels can fall to a twilit gloom or worse. For more than a week in the northern mid-latitude target zone, it might be much too dark to see, even at midday. In Cases 1 and 14 (Table 1), hemispherically averaged light levels fall to a few percent of normal values, comparable to those at the bottom of a dense overcast. At this illumination, many plants are close to what is called the compensation point, the light level at which photosynthesis can barely keep pace with plant metabolism. In Case 17, illumination, averaged over the entire Northern Hemisphere, falls in daytime to about 0.1 percent of normal, a light level at which plants will not photosynthesize at all. For Cases 1 and especially 17, full recovery to ordinary daylight takes a year or more (Figure 1).

As the fine particles fall out of the atmosphere, carrying radioactivity to the ground, the light levels increase and the surface warms. The depleted ozone layer now permits ultraviolet light to reach the Earth's surface in increased proportions. The relative timing of the multitude of adverse consequences of a nuclear war is shown in Table 2, on the following page.

Perhaps the most striking and unexpected consequence of our study is that even a comparatively small nuclear war can have devastating climatic consequences, provided cities are targeted (see Case 14 in Figure 1; here, the centers of 100 major NATO and Warsaw Pact cities are burning). There is an indication of a very rough threshold at which severe climatic consequences are triggered—around a few hundred nuclear explosions over cities, for smoke generation, or around 2,000 to 3,000 high-yield surface bursts at, e.g., missile silos, for dust generation and ancillary fires. Fine particles can be injected into the atmosphere at increasing rates with only minor effects until these thresholds are crossed. Thereafter, the effects rapidly increase in severity.[13]

As in all calculations of this complexity, there are uncertainties. Some factors tend to work towards more severe or more prolonged effects; others tend to ameliorate the effects.[14] The detailed TTAPS calculations described here are one-dimensional; that is, they assume the fine particles to move vertically by all the appropriate

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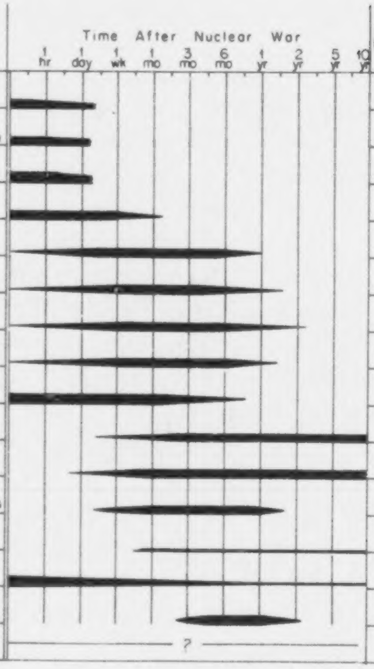
[13] The climatic threshold for smoke in the troposphere is about 100 million metric tons, injected essentially all at once; for sub-micron fine dust in the stratosphere, about the same.

[14] The slow warming of the Earth due to a CO_2 greenhouse effect attendant to the burning of fossil fuels should not be thought of as tempering the nuclear winter: the greenhouse temperature increments are too small and too slow.



Effect	U.S. / S.U. Population at risk	N.H. Population at risk	S.H. Population at risk	Casualty rate for those at risk	Potential global deaths
Blast	H	M	L	H	M - H
Thermal Radiation	H	M	L	M	M - H
Prompt Ionizing Radiation	L	L	L	H	L - M
Fires	M	M	L	M	M
Toxic Gases	M	M	L	L	L
Dark	H	H	M	L	L
Cold	H	H	H	H	M - H
Frozen Water Supplies	H	H	M	M	M
Fallout Ionizing Radiation	H	H	L - M	M	M - H
Food Shortages	H	H	H	H	H
Medical System Collapse	H	H	M	M	M
Contagious Diseases	M	M	L	H	M
Epidemics and Pandemics	H	H	M	M	M
Psychiatric Disorders	H	H	L	L	L - M
Increased Surface Ultraviolet Light	H	H	M	L	L
Synergisms	?	?	?	?	?

TABLE 2

EFFECTS OF THE BASELINE NUCLEAR WAR

NOTE: This is a schematic representation of the time scale for the effects, which are most severe when the thickness of the horizontal bar is greatest. The columns at the right indicate the degree of risk of the populations of the United States and the Soviet Union, the Northern Hemisphere, and the Southern Hemisphere—with H, M, and L standing for High, Medium, and Low respectively.

laws of physics, but neglect the spreading in latitude and longitude. When soot or dust is moved away from the reference locale, things get better there and worse elsewhere. In addition, fine particles can be transported by weather systems to other locales, where they are carried more rapidly down to the surface. That would ameliorate obscuration not just locally but globally. It is just this transport away from the northern mid-latitudes that involves the equatorial zone and the Southern Hemisphere in the effects of the nuclear war. It would be helpful to perform an accurate three-dimensional calculation on the general atmospheric circulation following a nuclear war. Preliminary estimates suggest that circulation might moderate the low temperatures in the Northern Hemisphere predicted in our calculations by some 30 percent, lessening somewhat the severity of the effects, but still leaving them at catastrophic levels (e.g., a 30°C rather than a 40°C temperature drop). To provide a small margin of safety, we neglect this correction in our subsequent discussion.

There are also effects that tend to make the results much worse: for example, in our calculations we assumed that rainout of fine particles occurred through the entire troposphere. But under realistic circumstances, at least the upper troposphere may be very dry, and any dust or soot carried there initially may take much longer to fall out. There is also a very significant effect deriving from the drastically altered structure of the atmosphere, brought about by the heating of the clouds and the cooling of the surface. This produces a region in which the temperature is approximately constant with altitude in the lower atmosphere and topped by a massive temperature inversion. Particles throughout the atmosphere would then be transported vertically very slowly—as in the present stratosphere. This is a second reason why the lifetime of the clouds of soot and dust may be much longer than we have calculated. If so, the worst of the cold and the dark might be prolonged for considerable periods of time, conceivably for more than a year. We also neglect this effect in subsequent discussion.

Nuclear war scenarios are possible that are much worse than the ones we have presented. For example, if command and control capabilities are lost early in the war—by, say, "decapitation" (an early surprise attack on civilian and military headquarters and communications facilities)—then the war conceivably could be extended for weeks as local commanders make separate and uncoordinated decisions. At least some of the delayed missile launches could be retaliatory strikes against any remaining adversary cities. Generation of an additional smoke pall over a period of weeks or longer following the initiation of the war would extend the magnitude, but especially the duration of the climatic consequences. Or it is possible that more cities and forests would be ignited than we have assumed, or that smoke emissions would be larger, or that a greater fraction of the world arsenals would be committed. Less severe cases are of course possible as well.

These calculations therefore are not, and cannot be, assured prognostications of the full consequences of a nuclear war. Many refinements in them are possible and are being pursued. But there is general agreement on the overall conclusions: in the wake of a nuclear war there is likely to be a period, lasting at least for months, of extreme cold in a radioactive gloom, followed—after the soot and dust fall out—by an extended period of increased ultraviolet light reaching the surface.[15]

We now explore the biological impact of such an assault on the global environment.

III

The immediate human consequences of nuclear explosions range from vaporization of populations near the hypocenter, to blast-generated trauma (from flying glass, falling beams, collapsing skyscrapers and the like), to burns, radiation sickness, shock and severe psychiatric disorders. But our concern here is with longer-term effects.

It is now a commonplace that in the burning of modern tall buildings, more people succumb to toxic gases than to fire. Ignition of many varieties of building materials, insulation and fabrics generates large amounts of such pyrotoxins, including carbon monoxide, cyanides, vinyl chlorides, oxides of nitrogen, ozone, dioxins, and furans. Because of differing practices in the use of such synthetics, the burning of cities in North America and Western Europe will probably generate more pyrotoxins than cities in the Soviet Union, and cities with substantial recent construction more than older, unreconstructed cities. In nuclear war scenarios in which a great many cities are burning, a significant pyrotoxin smog might persist for months. The magnitude of this danger is unknown.

The pyrotoxins, low light levels, radioactive fallout, subsequent ultraviolet light, and especially the cold are together likely to destroy almost all of Northern Hemisphere agriculture, even for the more modest Cases 11 and 14. A 12° to 15°C temperature reduction by itself would eliminate wheat and corn production in the United States, even if all civil systems and agricultural technology were intact.[16] With unavoidable societal disruption, and with the other environmental stresses just mentioned, even a 3,000-megaton "pure" counterforce attack (Case 11) might suffice. Realistically, many fires would be set even in such an attack (see below), and a 3,000-megaton war is likely to wipe out U.S. grain production. This would represent by itself an unprecedented global catastrophe: North American grain is the principal reliable source of export food on the planet, as well as an essential component of U.S. prosperity. Wars just before harvesting of grain and other staples would be incrementally worse than wars after harvesting. For many scenarios, the effects will extend (see Figure 2) into two or more growing seasons. Widespread fires and subsequent runoff of topsoil are among the many additional deleterious consequences extending for years after the war.

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[15] These results are dependent on important work by a large number of scientists who have previously examined aspects of this subject; many of these workers are acknowledged in the articles cited in footnote 1.

[16] David Pimentel and Mark Sorrells, private communication, 1983.

Something like three-quarters of the U.S. population lives in or near cities. In the cities themselves there is, on average, only about one week's supply of food. After a nuclear war it is conceivable that enough of present grain storage might survive to maintain, on some level, the present population for more than a year. But with the breakdown of civil order and transportation systems in the cold, the dark and the fallout, these stores would become largely inaccessible. Vast numbers of survivors would soon starve to death.

In addition, the sub-freezing temperatures imply, in many cases, the unavailability of fresh water. The ground will tend to be frozen to a depth of about a meter—incidentally making it unlikely that the hundreds of millions of dead bodies would be buried, even if the civil organization to do so existed. Fuel stores to melt snow and ice would be in short supply, and ice surfaces and freshly fallen snow would tend to be contaminated by radioactivity and pyrotoxins.

In the presence of excellent medical care, the average value of the acute lethal dose of ionizing radiation for healthy adults is about 450 rads. (As with many other effects, children, the infirm and the elderly tend to be more vulnerable.) Combined with the other assaults on survivors in the postwar environment, and in the probable absence of any significant medical care, the mean lethal acute dose is likely to decline to 350 rads or even lower. For many outdoor scenarios, doses within the fallout plumes that drift hundreds of kilometers downwind of targets are greater than the mean lethal dose. (For a 10,000-megaton war, this is true for more than 30 percent of northern mid-latitude land areas.) Far from targets, intermediate-timescale chronic doses from delayed radioactive fallout may be in excess of 100 rads for the baseline case. These calculations assume no detonations on nuclear reactors or fuel-reprocessing plants, which would increase the dose.

Thus, the combination of acute doses from prompt radioactive fallout, chronic doses from the delayed intermediate-timescale fallout, and internal doses from food and drink are together likely to kill many more by radiation sickness. Because of acute damage to bone marrow, survivors would have significantly increased vulnerability to infectious diseases. Most infants exposed to 100 rads as fetuses in the first two trimesters of pregnancy would suffer mental retardation and/or other serious birth defects. Radiation and some pyrotoxins would later produce neoplastic diseases and genetic damage. Livestock and domesticated animals, with fewer resources, vanishing food supplies and in many cases with greater sensitivity to the stresses of nuclear war than human beings, would also perish in large numbers.

These devastating consequences for humans and for agriculture would not be restricted to the locales in which the war would principally be "fought," but would extend throughout northern mid-latitudes and, with reduced but still significant severity, probably to the tropics and the Southern Hemisphere. The bulk of the world's grain exports originate in northern mid-latitudes. Many nations in the developing as well as the developed world depend on the import of food. Japan, for example, imports 75 percent of its food (and 99 percent of its fuel). Thus, even if there were no climatic and radiation stresses on tropical and Southern Hemisphere societies—many of them already at subsistence levels of nutrition—large numbers of people there would die of starvation.

As agriculture breaks down worldwide (possible initial exceptions might include Argentina, Australia and South Africa if the climatic impact on the Southern Hemisphere proved to be minimal), there will be increasing reliance on natural ecosystems--fruits, tubers, roots, nuts, etc. But wild foodstuffs will also have suffered from the effects of the war. At just the moment that surviving humans turn to the natural environment for the basis of life, that environment would be experiencing a devastation unprecedented in recent geological history.

Two-thirds of all species of plants, animals, and microorganisms on the Earth live within 25° of the equator. Because temperatures tend to vary with the seasons only minimally at tropical latitudes, species there are especially vulnerable to rapid temperature declines. In past major extinction events in the paleontological record, there has been a marked tendency for tropical organisms to show greater vulnerability than organisms living at more temperate latitudes.

The darkness alone may cause a collapse in the aquatic food chain in which sunlight is harvested by phytoplankton, phytoplankton by zooplankton, zooplankton by small fish, small fish by large fish, and, occasionally, large fish by humans. In many nuclear war scenarios, this food chain is likely to collapse at its base for at least a year and is significantly more imperiled in tropical waters. The increase in ultraviolet light available at the surface of the earth approximately a year after the war provides an additional major environmental stress that by itself has been described as having "profound consequences" for aquatic, terrestrial and other ecosystems.[17]

The global ecosystem can be considered an intricately woven fabric composed of threads contributed by the millions of separate species that inhabit the planet and interact with the air, the water and the soil. The system has developed considerable resiliency, so that pulling a single thread is unlikely to unravel the entire fabric. Thus, most ordinary assaults on the biosphere are unlikely to have catastrophic consequences. For example, because of natural small changes in stratospheric ozone abundance, organisms have probably experienced, in the fairly recent geologic past, ten percent fluctuations in the solar near-ultraviolet flux (but not fluctuations by factors of two or more). Similarly, major continental temperature changes of the magnitude and extent addressed here may not have been experienced for tens of thousands and possibly not for millions of years. We have no experimental information, even for aquaria or terraria, on the simultaneous effects of cold, dark, pyrotoxins, ionizing radiation, and ultraviolet light as predicted in the TTAPS study.

Each of these factors, taken separately, may carry serious consequences for the global ecosystem: their interactions may be much more dire still. Extremely worrisome is the possibility of poorly understood or as yet entirely uncontemplated synergisms (where the net consequences of two or more assaults on the environment are much more than the sum of the component parts). For example, more than 100 rads (and possibly more than 200 rads) of external and ingested ionizing radiation is likely to be delivered in a very large nuclear war to all plants, animals and unprotected humans in densely populated regions of northern mid-latitudes. After the soot and dust clear, there can, for such wars, be a 200 to 400 percent increment in the solar ultraviolet flux that reaches the ground, with an increase of many orders of magnitude in the more dangerous shorter-wavelength radiation. Together, these radiation assaults are likely to suppress the immune systems of humans and other species, making them more vulnerable to disease. At the same time, the high ambient-radiation fluxes are likely to produce, through mutation, new varieties of microorganisms, some of which might become pathogenic. The preferential radiation sensitivity of birds and other insect predators would enhance the proliferation of herbivorous and pathogen-carrying insects. Carried by vectors with high radiation tolerance, it seems possible that epidemics and global pandemics would propagate with no hope of effective mitigation by medical care, even with reduced population sizes and greatly restricted human mobility. Plants, weakened by low temperatures and low light levels, and other animals would likewise be vulnerable to preexisting and newly arisen pathogens.

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[17] C. H. Kruger, R. B. Setlow, *et al.*, *Causes and Effects of Stratospheric Ozone Reduction: An Update*, Washington: National Academy of Sciences, 1982.

There are many other conceivable synergisms, all of them still poorly understood because of the complexity of the global ecosystem. Every synergism represents an additional assault, of unknown magnitude, on the global ecosystem and its support functions for humans. What the world would look like after a nuclear war depends in part upon the unknown synergistic interaction of these various adverse effects.

We do not and cannot know that the worst would happen after a nuclear war. Perhaps there is some as yet undiscovered compensating effect or saving grace—although in the past, the overlooked effects in studies of nuclear war have almost always tended toward the worst. But in an uncertain matter of such gravity, it is wise to contemplate the worst, especially when its probability is not extremely small. The summary of the findings of the group of 40 distinguished biologists who met in April 1983 to assess the TTAPS conclusions is worthy of careful consideration:[18]

> Species extinction could be expected for most tropical plants and animals, and for most terrestrial vertebrates of north temperate regions, a large number of plants, and numerous freshwater and some marine organisms. . . . Whether any people would be able to persist for long in the face of highly modified biological communities; novel climates; high levels of radiation; shattered agricultural, social, and economic systems; extraordinary psychological stresses; and a host of other difficulties is open to question. It is clear that the ecosystem effects *alone* resulting from a large-scale thermonuclear war could be enough to destroy the current civilization in at least the Northern Hemisphere. Coupled with the direct casualties of perhaps two billion people, the combined intermediate and long-term effects of nuclear war suggest that eventually there might be no human survivors in the Northern Hemisphere.
>
> Furthermore, the scenario described here is by no means the most severe that could be imagined with present world nuclear arsenals and those contemplated for the near future. In almost any realistic case involving nuclear exchanges between the superpowers, global environmental changes sufficient to cause an extinction event equal to or more severe than that at the close of the Cretaceous when the dinosaurs and many other species died out are likely. In that event, the possibility of the extinction of *Homo sapiens* cannot be excluded.

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[18] P. Ehrlich, *et al.*, *loc. cit.* footnote 1.

IV

The foregoing probable consequences of various nuclear war scenarios have implications for doctrine and policy. Some have argued that the difference between the deaths of several hundred million people in a nuclear war (as has been thought until recently to be a reasonable upper limit) and the death of every person on Earth (as now seems possible) is only a matter of one order of magnitude. For me, the difference is considerably greater. Restricting our attention only to those who die as a consequence of the war conceals its full impact.

If we are required to calibrate extinction in numerical terms, I would be sure to include the number of people in future generations who would not be born. A nuclear war imperils all of our descendants, for as long as there will be humans. Even if the population remains static, with an average lifetime of the order of 100 years, over a typical time period for the biological evolution of a successful species (roughly ten million years), we are talking about some 500 trillion people yet to come. By this criterion, the stakes are one million times greater for extinction than for the more modest nuclear wars that kill "only" hundreds of millions of people.

There are many other possible measures of the potential loss—including culture and science, the evolutionary history of the planet, and the significance of the lives of all of our ancestors who contributed to the future of their descendants. Extinction is the undoing of the human enterprise.

For me, the new results on climatic catastrophe raise the stakes of nuclear war enormously. But I recognize that there are those, including some policymakers, who feel that the increased level of fatalities has little impact on policy, but who nevertheless acknowledge that the newly emerging consequences of nuclear war may require changes in specific points of strategic doctrine. I here set down what seem to me some of the more apparent such implications, within the context of present nuclear stockpiles. The idea of a crude threshold, very roughly around 500 to 2,000 warheads, for triggering the climatic catastrophe will be central to some of these considerations. (Such a threshold applies only to something like the present distribution of yields in the strategic arsenals. Drastic conversion to very low-yield arsenals—see below—changes some of the picture dramatically.) I hope others will constructively examine these preliminary thoughts and explore additional implications of the TTAPS results.

1. *First Strike*. The MIRVing of missiles (the introduction of mul-

tiple warheads), improvements in accuracy, and other developments have increased the perceived temptation to launch a devastating first strike against land targets—even though both sides retain a powerful retaliatory force in airborne bombers and submarines at sea. Much current concern and national rhetoric is addressed to the first-strike capability of extant or proposed weapons systems. The mere capability of a first strike creates incentives for a preemptive attack. Launch-on-warning and simultaneous release of all strategic weapons are two of several ominous and destabilizing innovations contrived in response to the fear of a first strike.

The number of U.S. land-based strategic missiles is about 1,050; for the Soviet Union, about 1,400. In addition, each side has at least several dozen dedicated and alternative strategic bomber bases and airstrips, as well as command and control facilities, submarine ports and other prime strategic targets on land. Each target requires—for high probability of its destruction—two or perhaps three attacking warheads. Thus, a convincing first strike against land targets requires at least 2,200 and perhaps as many as 4,500 attacking warheads. Some—for example, to disable bombers that succeed in becoming airborne just before the first strike—would detonate as airbursts. While many missile silos, especially in the United States, are surrounded by farmland and brush, other strategic targets, especially in Europe and Asia, are sufficiently near forests or urban areas for major conflagrations to be set, even in a "pure" counterforce attack. Accordingly, a major first strike would be clearly in the vicinity of, and perhaps well over, the climatic threshold.

A counterforce first strike is unlikely to be completely effective. Perhaps 10 to 40 percent of the adversary's silos and most of its airborne bombers and submarines at sea will survive, and *its* response may not be against silos, but against cities. Ten percent of a 5,000-warhead strategic arsenal is 500 warheads: distributed over cities, this seems by itself enough to trigger a major climatic catastrophe.

Such a first strike scenario, in which the danger to the aggressor nation depends upon the unpredictable response of the attacked nation, seems risky enough. (The hope for the aggressor nation is that its retained second-strike force, including strategic submarines and unlaunched land-based missiles, will intimidate the adversary into surrender rather than provoke it into retaliation.) But the decision to launch a first strike that is tantamount to national suicide for the aggressor—*even if the attacked nation does not lift a finger to retaliate*—is a different circumstance altogether. If a first strike gains no more than a pyrrhic victory of ten days' duration before the prevailing winds carry the nuclear winter to the aggressor nation, the "attractiveness" of the first strike would seem to be diminished significantly.

A Doomsday Machine is useless if the potential adversary is ignorant of its presence.[19] But since many distinguished scientists, both American and Soviet, have participated vigorously in recent studies of the climatic consequences of nuclear war, since there appears to be no significant disagreement in the conclusions, and since policymakers will doubtless be apprised of these new results, it would appear that a decision to launch a major first strike is now much less rational, and therefore, perhaps, much less probable. The better political leaders understand the nuclear winter, the more secure are such conclusions.

If true, this should have cascading consequences for specific weapons systems. Further, the perceived vulnerability to a first strike has been a major source of stress and fear, and thereby a major spur to the nuclear arms race. Knowledge that a first strike is now less probable might make at least some small contribution to dissipating the poisonous atmosphere of mistrust that currently characterizes Soviet-American relations.

2. *Sub-threshold War.* Devastating nuclear wars that are nevertheless significantly below the threshold for severe climatic consequences certainly seem possible—for example, the destruction of 10 or 20 cities, or 100 silos of a particularly destabilizing missile system. Nevertheless, might some nation be tempted to initiate or engage in a much larger, but still reliably sub-threshold nuclear war? The hope might be that the attacked adversary would be reluctant to retaliate for fear of crossing the threshold.

This is not very different from the hope that a counterforce first strike would not be followed by a retaliatory strike, because of the aggressor's retention of an invulnerable (for example, submarine-based) second-strike force adequate to destroy populations and national economies. It suffers the same deficiency—profound uncertainty about the likely response.

The strategic forces of the United States or the Soviet Union—even if they were all at fixed sites—could not be destroyed in a reliably sub-threshold war: there are too many essential targets. Thus, a sub-threshold first strike powerfully provokes the attacked nation and leaves much of its retaliatory force untouched. It is easy to imagine a nation, having contemplated becoming the object of a sub-threshold first strike, planning to respond in kind, because it judges that failure to do so would itself invite attack. Retaliation could occur immediately against a few key cities—if national leaders were restrained and command and control facilities intact—or massively, months later, after much of the dust and smoke have fallen out, extending the duration but ameliorating the severity of the net climatic effects.

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[19] The term "Doomsday Machine" is due to Herman Kahn, *Thinking About the Unthinkable*, New York: Horizon Press, 1962.

This, however, may not be the case for such nations as Britain, France or China. Because of the marked contiguity of strategic targets and urban areas in Europe, the climatic threshold for attacks on European nuclear powers may be significantly less than for the United States or the Soviet Union. Provided it could be accomplished without triggering a U.S.-Soviet nuclear war, first strikes against all the fixed-site strategic forces of one of these nations might not trigger the climatic catastrophe. Nevertheless, the invulnerable retaliatory capability of these nations—especially the ballistic-missile submarines of Britain and France—makes such a first strike unlikely.

3. *Treaties on Yields and Targeting.* I would not include this possibility, except that it has been mentioned publicly by a leading American nuclear strategist. The proposal has two parts. The first is to ban by treaty all nuclear warheads with yields in excess of 300 or 400 kilotons. The fireballs from warheads of higher yields mainly penetrate into the stratosphere and work to deplete the ozonosphere.

The reconversion of nuclear warheads to lower individual yields would reduce (although not remove) the threat of significantly enhanced ultraviolet radiation at the surface of the Earth, but would in itself have no bearing on the issue of climatic catastrophe, and would increase the intermediate-timescale radioactive fallout. Within the present strategic arsenals, there is no mix of yields that simultaneously minimizes ionizing radiation from fallout and ultraviolet radiation from the Sun.

As delivery system accuracy has progressively improved, there has been a corresponding tendency toward the deployment of lower-yield warheads, although not through any concern about the integrity of the ozonosphere. There is also a trend toward higher fission fractions, implying more radioactive fallout. Limitations on the sizes and therefore, to some extent, on the yields of new warheads are part of recent U.S. arms control proposals. With the bulk of Soviet strategic warheads having yields larger than their U.S. counterparts, however, treaties limiting high yields place greater demands on Soviet than on U.S. compliance. Moreover, to enforce a categorical yield ceiling seems to imply verification problems of some difficulty.

The second part of the proposal is to guarantee by treaty that cities would not be targeted. Then the worst of the climatic effects might be avoided, although the climatic consequences of "pure" counterforce exchanges can still be extremely serious (Figure 1). The encoding of targeting coordinates, however, is in principle done remotely, and involves different coordinates for each warhead. Even if we could imagine international inspection teams descending unannounced on Soviet or American missile silos to inspect the targeting coordinates, an hour later the coordinates could be returned to those appropriate for cities.

Targeting policy is among the most sensitive aspects of nuclear strategy, and maintaining uncertainty about targeting policy is thought to be an essential component of U.S. deterrence. The proposal is unlikely to be received warmly by the U.S. Joint Strategic Targeting Staff or its Soviet counterpart. It is also difficult to understand how those skeptical of the verifiability by reconnaissance satellites of SALT II provisions on the deployment of missiles ten meters long can rest easy about verification of treaties controlling what is encoded in a microchip one millimeter long. Nevertheless, a symbolic, unverifiable targeting treaty, entered into because both sides recognize that it is not in their interest to target cities, might have some merit.

4. *Transition to Low-Yield High-Accuracy Arsenals.* A conceivable response to the prospect of climatic catastrophe might be to continue present trends toward lower-yield and higher-accuracy missiles, perhaps accompanied by development of the technology for warheads to burrow sub-surface before detonating. Payloads have been developed for the Pershing II missile that use radar area-correlators for target recognition and terminal guidance; the targeting probable error is said to be 40 meters.[20] It is evident that a technology is gradually emerging that could permit delivery accuracies of 35 meters or better over intercontinental ranges.

It is evident as well that burrowing technology is also under rapid development.[21] A one-kiloton burst, two to three meters sub-surface, will excavate a crater roughly 60 meters across.[22] Clearly, high-accuracy penetrating warheads in the one-to-ten-kiloton range would be able, with high reliability, to destroy even very hardened silos and underground command posts.

[20] *Aviation Week and Space Technology*, May 15, 1978, p. 225.

[21] *Ibid.*

[22] S. Glasstone and P. J. Dolan, *op. cit.* footnote 2.

Low-yield sub-surface explosions of this sort cannot threaten the ozonosphere. They minimize fires, soot, stratospheric dust and radioactive fallout. Even several thousand simultaneous such detonations might not trigger the nuclear winter. Similar technology might be used for pinpoint attacks on military/industrial targets in urban areas. Thus, the TTAPS results will probably lead to calls for further improvements in high-accuracy earth-burrowing warheads.

There are, I think, a number of difficulties with this proposal, as attractive as it seems in a strictly military context. A world in which the nuclear arsenals were completely converted to a relatively small number of burrowing low-yield warheads would be much safer in terms of the climatic catastrophe. But such warheads are provocative. They are the perfect post-TTAPS first-strike weapon. Their development might well be taken as a serious interest in making a climatically safe but disabling first strike. Greatly expanded deployment of anti-ballistic missiles might be one consequence of their buildup.

Retaliation from surviving silos, aircraft and especially submarines, as discussed above, is likely, whatever the disposition of yields in a first strike. Also, arsenals cannot be converted instantaneously. There would be a very dangerous and protracted transition period in which enough newer weapons are deployed to be destabilizing, and enough older weapons are still in place to trigger the nuclear winter.

However, if the inventories of modern higher-yield (more than ten kiloton) warheads were first brought below threshold, a coordinated U.S.-Soviet deployment of low-yield burrowers might be accomplished in somewhat greater safety. On many launchers, each with a single warhead, they might provide a useful reassurance to defense ministries at some points in the transition process. At any rate, the dramatic reduction of arsenals necessary to go below threshold before large-scale burrower deployment is indistinguishable from major arms reduction for its own sake (see below).

5. *Consequences for the Developing World.* Before the TTAPS calculations were performed, it was possible to argue that the developing world would be severely affected by secondary economic consequences, but not fundamentally destroyed by a northern mid-latitude nuclear war. Now it seems more likely that nations having no part in the conflict—even nations entirely neutral in the global confrontation between the United States and the Soviet Union—might be reduced to prehistoric population levels and economies, or worse. Nations between 70°N and 30°S, nations with marginal economies, nations with large food imports or extensive malnutri-

tion today, and nations with their own strategic targets are particularly at risk.

Thus, the very survival of nations distant from any likely nuclear conflict can now be seen to depend on the prudence and wisdom of the major nuclear powers. India, Brazil, Nigeria or Saudi Arabia could collapse in a nuclear war without a single bomb being dropped on their territories.[23]

Quite apart from any concern about the deflection of world financial, technical and intellectual resources to the nuclear arms race, the prospect of nuclear war now clearly and visibly threatens every nation and every person on the planet. The diplomatic and economic pressure accordingly placed on the five nuclear powers by the other nations of the world, concerned about their own survival, could be at least marginally significant.

6. *Shelters.* The usual sorts of shelters envisioned for civilian populations are ineffective even for the nuclear war consequences known before the TTAPS study. The more ambitious among them include food and water for a week or two, modest heating capabilities, rudimentary sanitary and air filtration facilities and no provisions for the psychological burdens of an extended stay below ground with unknown climatic and ecological consequences propagating overhead. The kinds of shelters suitable for prolonged subfreezing temperatures, high radiation doses, and pyrotoxins would have to be very much more elaborate—quite apart from the question of what good it would be to emerge six or nine months later to an ultraviolet-bathed and biologically depauperate surface, with insect pests proliferating, disease rampant, and the basis of agriculture destroyed.

Appropriate shelters, able to service individual families or family groups for months to a year, are too expensive for most families even in the affluent West. The construction of major government shelters for civilian populations would be enormously expensive as well as in itself potentially destabilizing. The prospect of the climatic catastrophe also heightens the perceived inequity between government leaders and (in some cases) their families, provided elaborate shelters, and the bulk of the civilian population, unable to afford even a minimally adequate shelter.

[23] The distribution of the coldest regions will vary with time and geography. In one recent but still very crude three-dimensional simulation of the nuclear winter, the temperature has, by 40 days after the war, dropped by 15 to more than 40 centigrade degrees over much of the globe, including a vast region extending from Chad to Novosibirsk, from the Caspian Sea to Sri Lanka, embracing India, Pakistan and western China, and having its most severe effects in Afghanistan, Iran and Saudi Arabia. V. V. Alexandrov and G. L. Stenchikov, preprint, Computing Center, U.S.S.R. Academy of Sciences, Moscow, 1983.

But even if it were possible to build perfectly effective shelters for the entire populations of the United States and the Soviet Union, this would in no way address the danger to which the rest of the world would be put. Shelters for the combatant nations under circumstances in which only their citizens are threatened are one thing. Shelters for the combatant nations when gravely threatened noncombatant nations have only rudimentary or nonexistent shelters are a very different matter.

7. *Ballistic-Missile Defense Systems.* It might be argued that the prospect of a climatic catastrophe strengthens whatever arguments there may be for ground-based or space-based ballistic missile defense (BMD) systems, as proposed by President Reagan in his March 23, 1983 "Star Wars" speech. There are grave technical, cost and policy difficulties with such proposals.[24] Even advocates do not envision it being fully operational in less than two or three decades.

Optimistic informed estimates of porosity or "penetrance" (the fraction of attacking missiles successfully detonating at their targets despite the BMD) are no lower than 5 to 30 percent. The present world arsenal of strategic warheads is so much greater than the threshold for climatic catastrophe that, even if 5 to 30 percent of attacking missiles get through in something like a full exchange, the catastrophe could be triggered. And most competent estimates put the porosity—at least for the foreseeable future—at 50 percent to 99 percent. Further, one likely response to an adversary's anticipated deployment of BMD systems would be a proportionate increase in the stockpiles of offensive warheads in compensation.

There are three phases in the trajectories of incoming missiles when they might be attacked: boost phase, midcourse phase, and terminal phase. Boost-phase and midcourse interception would, at best, require an untried technology deployed at scales never before attempted. Only terminal-phase BMDs exist at the present time (antiballistic missiles or ABMs), and even they, ineffective as they are, may require ruinous capital investments before they can provide meaningful levels of defense. Developments in terminal-phase maneuverability of attacking warheads are likely to raise the price tag of an effective BMD sharply again. Even in the best of circumstances, offense will be more effective and less costly than defense.

Finally, terminal-phase interception, generally effective only for hard-target defense, is characteristically designed to occur at very low altitudes. There would be an advantage to the offense if it fused the incoming missiles so they would explode if attacked ("sympathetic detonation"). In some schemes, the BMD itself involves nuclear warheads exploded near the ground. A fair fraction of hard targets, especially in Europe and the Soviet Union, are within a few tens of kilometers of cities or forests. Thus, the most readily deployable BMD suffers the disability, when it works at all, of generating fires contributory to a climatic catastrophe, quite apart from its porosity.

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[24] Richard Garwin, testimony before the Subcommittee on International Security and Scientific Affairs of the House Committee on Foreign Affairs, U.S. Congress, November 10. 1983; Hans Bethe, manuscript in preparation.

8. *Other Possibilities.* There are a number of other conceivable responses to the climatic catastrophe, some even more desperate than those discussed above. For example, a nation might relocate its silos and mobile launchers (the latter inviting barrage attack) to cities and forests to guarantee that a barely adequate counterforce first strike by its adversary would trigger a global climatic catastrophe with high confidence. Or nations with small nuclear arsenals or marginal strategic capability might contemplate amassing a threshold arsenal of some 500 to 2,000 deliverable warheads in order to be taken seriously in "great power" politics.

But these and similar contrivances increase the probability of nuclear war or the dangers attendant to nuclear war sufficiently that they are likely to be rejected by the nation contemplating such moves or, failing that, by other nations. Major relocations of strategic weapons systems or the deployment of new strategic arsenals are readily detectable by national technical means.

V

None of the foregoing possible strategic and policy responses to the prospect of a nuclear war-triggered climatic catastrophe seem adequate even for the security of the nuclear powers, much less for the rest of the world. The prospect reinforces, in the short run, the standard arguments for strategic confidence-building, especially between the United States and the Soviet Union; for tempering puerile rhetoric; for resisting the temptation to demonize the adversary; for reducing the likelihood of strategic confrontations arising from accident or miscalculation; for stabilizing old and new weapons systems—for example, by de-MIRVing missiles; for abandoning nuclear-war-fighting strategies and mistrusting the possibility of "containment" of a tactical or limited nuclear war; for considering safe unilateral steps, such as the retiring of some old weapons systems with very high-yield warheads; for improving communications at all levels, especially among general staffs and between heads of governments; and for public declarations of relevant policy changes. The United States might also contemplate ratification of SALT II and of the 1948 U.N. Convention on the Prevention and Punishment of the Crime of Genocide (ratified by 92 nations, including the Soviet Union).

Both nations might consider abandoning apocalyptic threats and doctrines. To the extent that these are not credible, they undermine deterrence; to the extent that they are credible, they set in motion events that tend toward apocalyptic conclusions.

In the long run, the prospect of climatic catastrophe raises real questions about what is meant by national and international security. To me, it seems clear that the species is in grave danger at least until the world arsenals are reduced below the threshold for climatic catastrophe; the nations and the global civilization would remain vulnerable even at lower inventories. It may even be that, now, the only credible arsenal is below threshold. George Kennan's celebrated proposal[25] to reduce the world arsenals initially to 50 percent of their current numbers is recognized as hard enough to implement. But it would be only the first step toward what is now clearly and urgently needed—a more than 90-percent reduction (Kennan proposed an ultimate reduction of more than 84 percent—adequate for strategic deterrence, if that is considered essential, but unlikely to trigger the nuclear winter. Still further reductions could then be contemplated.

The detonation of weapons stockpiles near or above threshold would be, we can now recognize, in contravention of the 1977 Geneva Convention on The Hostile Use of Environmental Modification Techniques, signed by 48 nations and duly ratified by the Soviet Union and the United States.[26] And Article 6 of the 1968 Nuclear Non-Proliferation Treaty requires the United States and the Soviet Union, among other signatory states, "to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament. . . ." I do not imagine that these treaties can, by themselves, play a determining role in producing major reductions in the world strategic arsenals, but they establish some sense of international obligation and can at least expedite urgent bilateral and multilateral consultations.

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[25] George F. Kennan, "The Only Way Out of the Nuclear Nightmare," *Manchester Guardian Weekly*, May 31, 1981. This is Kennan's acceptance speech for the Albert Einstein Peace Prize on May 19, 1981, in Washington, D.C.

[26] Article 1, paragraph 1, states: "Each State Party to this Convention undertakes not to engage in military or any other hostile use of environmental modification techniques having widespread, long-lasting or severe effects as the means of destruction, damage, or injury to another State Party." Paragraph 2 goes on: "Each State Party to this Convention undertakes not to assist, encourage or induce any State, group of States or international organization to engage in activities contrary to the provisions of paragraph 1 . . ."

VI

We have, by slow and imperceptible steps, been constructing a Doomsday Machine. Until recently—and then, only by accident—no one even noticed. And we have distributed its triggers all over the Northern Hemisphere. Every American and Soviet leader since 1945 has made critical decisions regarding nuclear war in total ignorance of the climatic catastrophe. Perhaps this knowledge would have moderated the subsequent course of world events and, especially, the nuclear arms race. Today, at least, we have no excuse for failing to factor the catastrophe into long-term decisions on strategic policy.

Since it is the soot produced by urban fires that is the most sensitive trigger of the climatic catastrophe, and since such fires can be ignited even by low-yield strategic weapons, it appears that the most critical ready index of the world nuclear arsenals, in terms of climatic change, may be the total *number* of strategic warheads. (There is some dependence on yield, to be sure, and future very low-yield, high-accuracy burrowing warheads could destroy strategic targets without triggering the nuclear winter, as discussed above.) For other purposes there are other indices—numbers of submarine-launched warheads, throw-weight (net payload deliverable to target), total megatonnage, etc. From different choices of such indices, different conclusions about strategic parity can be drawn. In the total number of strategic warheads, however, the United States is "ahead" of the Soviet Union and always has been.

Very roughly, the level of the world strategic arsenals necessary to induce the climatic catastrophe seems to be somewhere around 500 to 2,000 warheads—an estimate that may be somewhat high for airbursts over cities, and somewhat low for high-yield groundbursts. The intrinsic uncertainty in this number is itself of strategic importance, and prudent policy would assume a value below the low end of the plausible range.

National or global inventories above this rough threshold move the world arsenals into a region that might be called the "Doomsday Zone." If the world arsenals were well below this rough threshold, no concatenation of computer malfunction, carelessness, unauthorized acts, communications failure, miscalculation and madness in high office could unleash the nuclear winter. When global arsenals are above the threshold, such a catastrophe is at least possible. The further above threshold we are, the more likely it is that a major exchange would trigger the climatic catastrophe.

Traditional belief and childhood experience teach that more weapons buy more security. But since the advent of nuclear weapons and the acquisition of a capacity for "overkill," the possibility has arisen that, past a certain point, more nuclear weapons do not increase national security. I wish here to suggest that, beyond the climatic threshold, an increase in the number of strategic weapons leads to a pronounced *decline* in national (and global) security. National security is not a zero-sum game. Strategic insecurity of one adversary almost always means strategic insecurity for the other. Conventional pre-1945 wisdom, no matter how deeply felt, is not an adequate guide in an age of apocalyptic weapons.

If we are content with world inventories above the threshold, we are saying that it is safe to trust the fate of our global civilization and perhaps our species to all leaders, civilian and military, of all present and future major nuclear powers; and to the command and control efficiency and technical reliability in those nations now and in the indefinite future. For myself, I would far rather have a world in which the climatic catastrophe cannot happen, independent of the vicissitudes of leaders, institutions and machines. This seems to me elementary planetary hygiene, as well as elementary patriotism.

Something like a thousand warheads (or a few hundred megatons) is of the same order as the arsenals that were publicly announced in the 1950s and 1960s as an unmistakable strategic deterrent, and as sufficient to destroy either the United States or the Soviet Union "irrecoverably." Considerably smaller arsenals would, with present improvements in accuracy and reliability, probably suffice. Thus it is possible to contemplate a world in which the global strategic arsenals are below threshold, where mutual deterrence is in effect to discourage the use of those surviving warheads, and where, in the unhappy event that some warheads are detonated, there is little likelihood of the climatic catastrophe.[27]

To achieve so dramatic a decline in the global arsenals will require not only heroic measures by both the United States and the Soviet Union—it will also require consistent action by Britain, France and China, especially when the U.S. and Soviet arsenals are significantly reduced. Currently proposed increments in the arsenals at least of France would bring that nation's warhead inventory near or above threshold. I have already remarked on the strategic instability, in the context of the climatic catastrophe only, of the warhead inventories of these nations. But if major cuts in the U.S. and Soviet arsenals were under way, it is not too much to hope that the other major powers would, after negotiations, follow suit. These considerations also underscore the danger of nuclear weapons proliferation to other nations, especially when the major inventories are in steep decline.

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[27] Since higher-yield tactical warheads can also be used to burn cities, and might do so inadvertently, especially in Europe, provision for their elimination should also eventually be made. But initial attention should be directed to strategic warheads and their delivery systems.

Figure 2, on the following page, illustrates the growth of the American and Soviet strategic inventories from 1945 to the present.[28] To minimize confusion in the Figure, the British, French and Chinese arsenals are not shown; they are, however, as just mentioned, significant on the new scale of climatically dangerous arsenals. We see from the Figure that the United States passed the Doomsday Threshold around 1953, and the Soviet Union not until about 1966. The largest disparity in the arsenals was in 1961 (a difference of some 6,000 warheads). At the present time the disparity is less than it has been in any year since 1955. A published extrapolation of the present strategic arsenals into 1985 is shown as dashed, nearly vertical lines, accommodating new U.S. (Pershing II, cruise, MX and Trident) and Soviet (SS-21, -22, -23) strategic systems. If these extrapolations are valid, the United States and the Soviet Union would have almost identical numbers of inventories by the late 1980s.

The uppermost (dash-dot) curve in Figure 2 shows the total U.S. and Soviet arsenals (essentially the world arsenals) climbing upward since about 1970 with a very steep slope, the slope steepening still more if the projection is valid. Such exponential or near-exponential runaways are expected in arms races where each side's rate of growth is proportional to its perception of the adversary's weapons inventory; but it is likewise clear that such rapid growth cannot

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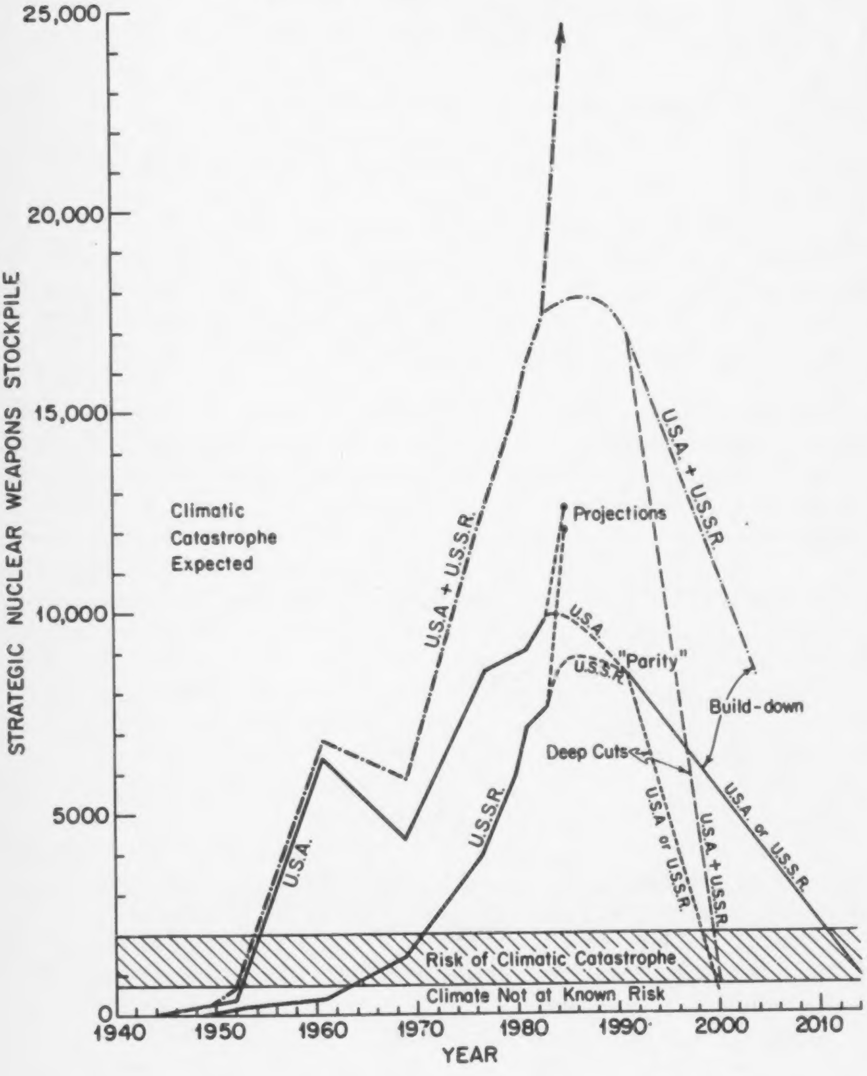
[28] The total warheads calculated in Figure 2 include strategic and theater weapons, but not tactical weapons. Not all published sources are in perfect agreement on these numbers. The principal sources used here are the *Report of the Secretary of Defense [Harold Brown] to the Congress on the FY 1982 Budget, FY 1983 Authorization Request* and *FY 1986 Defense Programs*, Washington: Department of Defense, 1981; and *National Defense Budget Estimates, FY 1983*, Office of the Assistant Secretary of Defense, Comptroller, March 1982.

Beyond 1983, projected increases in arsenals are shown for U.S. and Soviet arsenals as nearly vertical dashed lines, with the sum of these arsenals as the line at the top of the Figure terminating in an arrowhead. The data are from Frank Barnaby in the special issue of *Ambio* cited in footnote 5, pp. 76–83. See also *Counterforce Issues for the U.S. Strategic Nuclear Forces*, Congressional Budget Office, January 1978.

Figure 2 shows three regions: an upper region in which the nuclear winter could almost certainly be triggered; a lower region at which it could not be triggered; and a transition zone, shown shaded. The boundaries of this transition zone are more uncertain than shown, and depend among other things on targeting strategy. But the threshold probably lies between several hundred and a few thousand contempory strategic weapons.

FIGURE 2
PAST AND FUTURE NUCLEAR STOCKPILES



continue indefinitely. In all natural and human systems, such steep growth rates are eventually stopped, often catastrophically.

It is widely agreed—although different people have different justifications for this conclusion—that world arsenals must be reduced significantly. There is also general agreement, with a few demurrers, that at least the early and middle stages of a significant decline can be verified by national technical means and other procedures. The first stage of major arms reduction will have to overcome a new source of reluctance, when almost all silos could be reliably destroyed in a sub-threshold first strike. To overcome this reluctance, both sides will have prudently maintained an invulnerable retaliatory force, which itself would later move to sub-threshold levels. (It would even be advantageous to each nation to provide certain assistance in the development of such a force by the other.)

As arsenals are reduced still further, the fine tuning of the continuing decline may have to be worked out very carefully and with additional safeguards to guarantee continuing rough strategic parity. As threshold inventories are approached, some verifiable upper limits on yields as well as numbers would have to be worked out, to minimize the burning of cities if a nuclear conflict erupted. On the other hand, the deceleration of the arms race would have an inertia of its own, as the acceleration does; and successful first steps would create a climate conducive to subsequent steps.

There are three proposals now prominently discussed in the United States: Nuclear Freeze, Build-Down, and Deep Cuts. Their possible effects are diagrammed in Figure 2. They are by no means mutually exclusive, nor do they exhaust the possible approaches. A negotiated Freeze would at least prevent the continuing upward escalation in stockpiles, would forestall the deployment of more destabilizing systems, and would probably be accompanied by agreement on immediate annual phased reductions (the curved lines in the middle to late 1980s in Figure 2). To reduce the perceived temptation for a first strike, de-MIRVing of missiles during arms reduction may be essential.

The most commonly cited method of following the Freeze with reductions is incorporated in the Kennedy-Hatfield Freeze Resolution: percentage reductions. Under this approach, the two sides would agree on a percentage—often quoted as being between five percent and ten percent—and would agree to decrease deployed warheads by that percentage annually. The percentage reduction method was proposed to the Soviet Union by the United States at the Vienna Summit in June 1979 and was to be applied to the limits and sub-limits of the SALT II accords until these reached a reduction of 50 percent.

The Build-Down proposal is one in which modernization is permitted, but each side must pay a price in additional reductions of warheads for each warhead mounted on a modernized missile. In many current versions of the proposal, it would also require both sides to decrease their total warhead inventories by about five percent a year (again, the percentage annual reduction approach), to ensure that at least some reductions would take place even if modernization did not. The rate of decline for Build-Down illustrated in Figure 2 is essentially that of Representative Albert Gore (D.-Tenn.), in which rough parity at 8,500 warheads each is adopted as a goal for 1991–92, and the levels are reduced to 6,500 warheads each by 1997.[29]

There is concern that the "modernization" of strategic systems that Build-Down encourages might open the door to still more destabilizing weapons. It is also by no means clear that all proponents of Build-Down envision further reductions below the interim goal of about 5,000 warheads each for the United States and Soviet Union. If this rate of Build-Down continued indefinitely, the two nations would not cross back below threshold until about the year 2020. As dramatic a change from the present circumstances as this represents, in light of the present global crisis, it is, I think, too leisurely a pace.

Deep Cuts, originally advocated by George Kennan and Noel Gayler[30] as an initial halving of the global arsenals in some relatively short period of time, proposes the turning in of the fission triggers of thermonuclear weapons, deployed or undeployed, to a binational or multinational authority, with the triggers subsequently gainfully consumed in nuclear power plants (the ultimate in beating swords into plowshares). A highly schematic curve for something like Deep Cuts is also shown in Figure 2, starting from Gore's assumption of parity by 1991–92. Halving of the present global arsenals would then occur around 1995, and the global arsenals would return to below the Doomsday Threshold by the year 2000.

The actual shape of these declining curves would very likely have kinks and wiggles in them to accommodate the details of a bilaterally—and eventually multilaterally—agreed-upon plan to reduce the arsenals without compromising the security of any of the nuclear powers. The Deep Cuts curve shown has a rate of decline only about as steep as the rate of rise beginning in 1970. Much steeper declines may be feasible and should be considered.

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[29] *Congressional Record*, August 4, 1983, Vol. 129, No. 114.

[30] George F. Kennan, *loc. cit.* footnote 24; Noel Gayler, "How to Break the Momentum of the Nuclear Arms Race," *The New York Times Magazine*, April 25, 1982.

No one contends it will be easy to reverse the nuclear arms race. It is required at least for the same reasons that were used to justify the arms race in the first place—the national security of the United States and the Soviet Union. It is necessarily an enterprise of great magnitude. John Stuart Mill said: "Against a great evil, a small remedy does not produce a small result. It produces no result at all." But if the same technical ingenuity, dedication and resources were devoted to the downward slopes in Figure 2 as to the upward slopes, there is no reason to doubt that it could be negotiated safely.

In the deployment of more stabilizing weapons systems, in the possible development—especially in later stages of arms reductions—of novel means of treaty verification, and (perhaps) in the augmentation of conventional armaments, it will, of course, be expensive.

But, given the stakes, a prudent nuclear power should be willing to spend more every year to defuse the arms race and prevent nuclear war than it does on all military preparedness. For comparison, in the United States the annual budget of the Department of Defense is about 10,000 times that of the Arms Control and Disarmament Agency, quite apart from any questions about the dedication and effectiveness of the ACDA. The equivalent disparity is even greater in many other nations. I believe that the technical side of guaranteeing a major multilateral and strategically secure global arms reduction can be devised and deployed for considerably less—perhaps even a factor of 100 less—than the planet's direct military expenditures of $540 billion per year.[31]

Such figures give some feeling for the chasm that separates a prudent policy in face of our present knowledge of nuclear war from the actual present policies of the nuclear powers. Likewise, nations far removed from the conflict, even nations with little or no investment in the quarrels among the nuclear powers, stand to be destroyed in a nuclear war, rather than benefiting from the mutual annihilation of the superpowers.. They too, one might think, would be wise to devote considerable resources to help ensure that nuclear war does not break out.

VII

In summary, cold, dark, radioactivity, pyrotoxins and ultraviolet light following a nuclear war—including some scenarios involving only a small fraction of the world strategic arsenals—would imperil every survivor on the planet. There is a real danger of the extinction of humanity. A threshold exists at which the climatic catastrophe could be triggered, very roughly around 500–2,000 strategic warheads. A major first strike may be an act of national suicide, even if no retaliation occurs. Given the magnitude of the potential loss, no policy declarations and no mechanical safeguards can adequately guarantee the safety of the human species. No national rivalry or ideological confrontation justifies putting the species at risk. Accordingly, there is a critical need for safe and verifiable reductions of the world strategic inventories to below threshold. At such levels, still adequate for deterrence, at least the worst could not happen should a nuclear war break out.

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[31] Ruth Leger Sivard, *World Military and Social Expenditures*, Leesburg (Va.): World Priorities, 1983.

National security policies that seem prudent or even successful during a term of office or a tour of duty may work to endanger national—and global—security over longer periods of time. In many respects it is just such short-term thinking that is responsible for the present world crisis. The looming prospect of the climatic catastrophe makes short-term thinking even more dangerous. The past has been the enemy of the present, and the present the enemy of the future.

The problem cries out for an ecumenical perspective that rises above cant, doctrine and mutual recrimination, however apparently justified, and that at least partly transcends parochial fealties in time and space. What is urgently required is a coherent, mutually agreed upon, long-term policy for dramatic reductions in nuclear armaments, and a deep commitment, embracing decades, to carry it out.

Our talent, while imperfect, to foresee the future consequences of our present actions and to change our course appropriately is a hallmark of the human species, and one of the chief reasons for our success over the past million years. Our future depends entirely on how quickly and how broadly we can refine this talent. We should plan for and cherish our fragile world as we do our children and our grandchildren: there will be no other place for them to live. It is nowhere ordained that we must remain in bondage to nuclear weapons.

Established 1845 SCIENTIFIC AMERICAN August 1984 Volume 251 Number 2

The Climatic Effects of Nuclear War

New findings tend to support the view that the immense clouds of smoke and dust raised by even a medium-scale nuclear war could bring about a global "nuclear winter"

by Richard P. Turco, Owen B. Toon, Thomas P. Ackerman, James B. Pollack and Carl Sagan

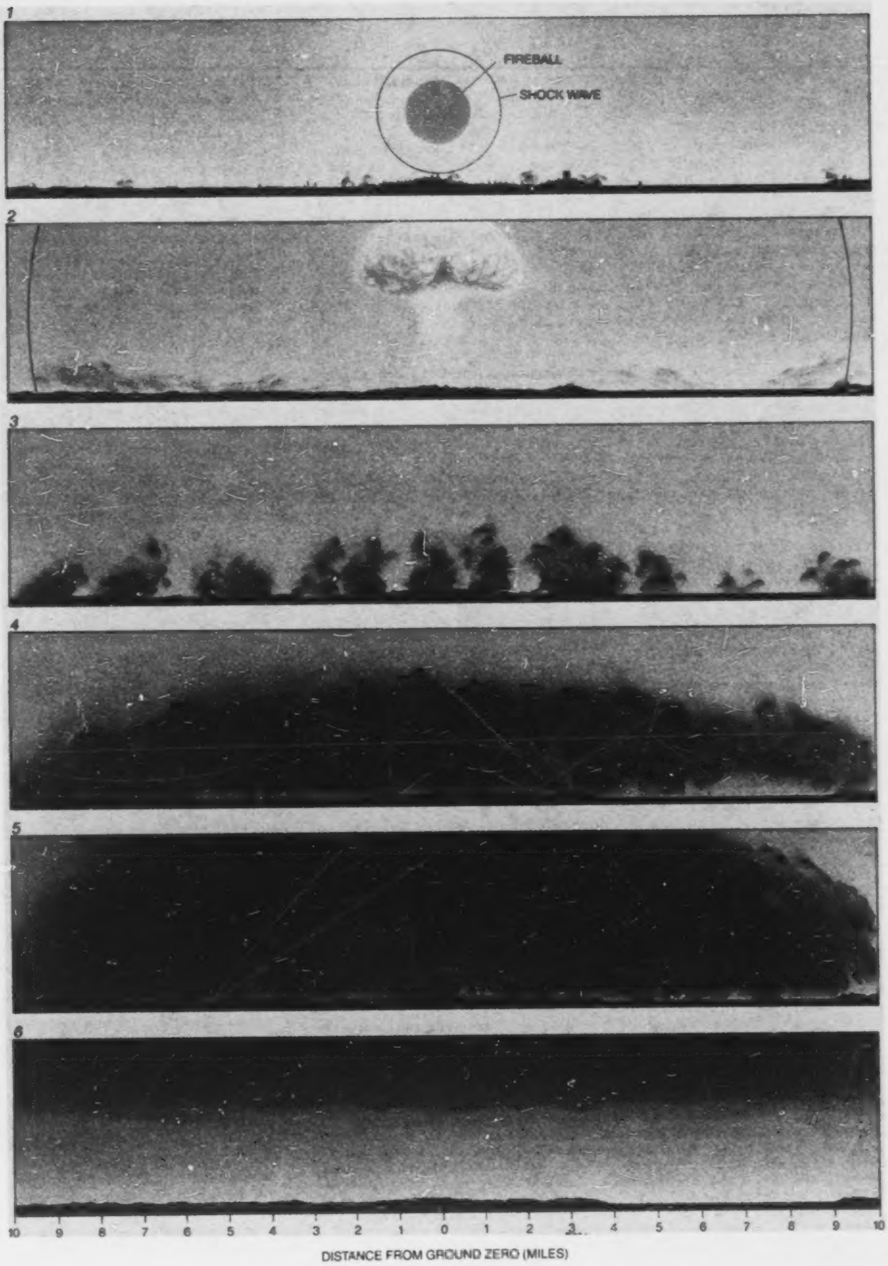
Since the beginning of the nuclear arms race four decades ago it has been generally assumed that the most devastating consequence of a major nuclear war between the U.S. and the U.S.S.R. would be a gigantic number of human casualties in the principal target zones of the Northern Hemisphere. Although in the wake of such a war the social and economic structure of the combatant nations would presumably collapse, it has been argued that most of the noncombatant nations—and hence the majority of the human population—would not be endangered, either directly or indirectly. Over the years questions have been raised about the possible global extent of various indirect, long-term effects of nuclear war, such as delayed radioactive fallout, depletion of the protective ozone layer in the upper atmosphere and adverse changes in the climate. Until recently, however, the few authoritative studies available on these added threats have tended to play down their significance, in some cases emphasizing the uncertainty inherent in any attempt to predict the combined effects of multiple nuclear explosions.

This comparatively optimistic view of the potential global impact of nuclear war may now have to be revised. Recent findings by our group, confirmed by workers in Europe, the U.S. and the U.S.S.R., suggest that the long-term climatic effects of a major nuclear war are likely to be much severer and farther-reaching than had been supposed. In the aftermath of such a war vast areas of the earth could be subjected to prolonged darkness, abnormally low temperatures, violent windstorms, toxic smog and persistent radioactive fallout—in short, the combination of conditions that has come to be known as "nuclear winter." The physical effects of nuclear war would be compounded by the widespread breakdown of transportation systems, power grids, agricultural production, food processing, medical care, sanitation, civil services and central government. Even in regions far from the conflict the survivors would be imperiled by starvation, hypothermia, radiation sickness, weakening of the human immune system, epidemics and other dire consequences. Under some circumstances, a number of biologists and ecologists contend, the extinction of many species of organisms—including the human species—is a real possibility.

Our own involvement in the reassessment of the global effects of nuclear war originated in a confluence of several lines of inquiry. Before joining forces we had separately and collectively been engaged in research on such phenomena as dust storms on Mars and the climatic effects of explosive volcanic eruptions on the earth; more recently we all became interested in the hypothesis that one or more of the mass extinctions of species evident in the geologic record were caused by immense clouds of dust raised by the impact of an asteroid or a comet. In 1982 a committee of the National Academy of Sciences, recognizing the parallels between the dust raised by nuclear explosions and that raised by other cataclysmic events, such as volcanic eruptions and meteorite impacts, asked us to look into the possible climatic effects of the dust likely to result from a nuclear war. We had already been considering the question, and to address it further we had at our disposal sophisticated computer models of both large- and small-scale atmospheric phenomena; the models had been developed over the preceding decade primarily to study the origins, properties and effects of particles in the atmosphere.

At about the same time another important aspect of the question came to our attention. An article in the Swedish environmental journal *Ambio*, coauthored by Paul J. Crutzen of the Max Planck Institute for Chemistry at Mainz in West Germany and John W. Birks of the University of Colorado at Boulder, pointed out that fires ignited by nuclear explosions could generate massive amounts of smoke, severely attenuating the sunlight reaching the ground. Accordingly we added smoke to dust as a likely perturbing influence of nuclear war on the climate.

In brief, our initial results, published in *Science* in December, 1983, showed that "the potential global atmospheric and climatic consequences of nuclear war... are serious. Significant hemispherical attenuation of the solar radiation flux and subfreezing land temperatures may be caused by fine dust raised in high-yield nuclear surface bursts and by smoke from city and forest fires ignited by airbursts of all yields." Moreover, we found that long-term exposure to nuclear radiation from the radioactive fallout of a nuclear war in the Northern Hemisphere could be an order of magnitude greater than previous studies had indicated; the radioactivity, like the other nuclear-winter effects, could even extend deep into the Southern Hemisphere. "When combined with the prompt destruction from nuclear blast, fires and fallout and the later enhancement of solar ultraviolet radiation due to ozone depletion," we concluded, "long-term exposure to cold, dark and radioactivity could pose a serious threat to human survivors and to other species." Subsequent studies, based on more powerful models of the general circulation of the earth's atmosphere, have tended to confirm both the validity


1
FIREBALL
SHOCK WAVE
2
3
4
5
6
10 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 10
DISTANCE FROM GROUND ZERO (MILES)

of our investigative approach and the main thrust of our findings. In what follows we shall review the current state of knowledge on this vital issue.

Before one can understand the climatic effects of nuclear war one must first understand how the earth's radiation budget is normally balanced. The amount of sunlight absorbed by the atmosphere and the surface of the earth, averaged over time, is equal to the amount of thermal radiation emitted back into space. Because the intensity of the thermal radiation varies as the fourth power of the temperature, both the surface temperature and the atmospheric temperature can adjust fairly quickly to maintain the overall energy balance between the solar energy gained and the thermal energy lost.

If the earth were an airless body like the moon, its surface would radiate the absorbed solar energy directly into space. In this case the globally averaged temperature of the earth would be well below the freezing point of water, and life as we know it could not exist on our planet. Fortunately the earth has an atmosphere, which absorbs and traps some of the heat emitted by the surface, thereby raising the average ground-level temperature to well above freezing and providing a favorable environment for forms of life, such as ours, that are based on liquid water.

The thermal insulation of the earth's surface by the atmosphere—the "greenhouse effect"—arises from the fact that sunlight passes through the atmosphere more readily than thermal radiation does. The radiation emitted by the sun is mainly in the visible part of the electromagnetic spectrum, whereas the thermal radiation emitted by the earth's surface is concentrated in the infrared part. The main infrared-absorbing components of the atmosphere are water (in the form of ice crystals, liquid droplets and vapor) and carbon dioxide gas, both of which are essentially transparent to visible light. Hence the atmosphere generally acts as a window for sunlight but as a blanket for heat.

Under normal conditions the temperature of the troposphere, or lower atmosphere, decreases gradually with increasing altitude up to a height of about 12 kilometers, the boundary called the tropopause. Heat from the earth's surface is transferred upward through the atmosphere by several mechanisms: thermal radiation, small-scale turbulence, large-scale convection and the release of latent heat through the condensation of ascending water vapor. In a purely radiative atmosphere (that is, one in which the air does not move vertically and all the energy is transferred by radiation) the lower layers of air, where most of the solar energy is absorbed, would be warmer than the higher layers; in this situation the upward thermal radiation would exceed the downward thermal radiation, allowing the excess heat to escape into space. If the opacity of the atmosphere to infrared radiation were to increase (with no change in the opacity to visible light), the temperature would increase. For example, if carbon dioxide, a good infrared absorber, were added to the atmosphere in sufficient quantities, it would warm the surface.

Conversely, if some component of the atmosphere were to reduce the amount of sunlight reaching the surface without significantly increasing the infrared opacity, the ground temperature would decrease. For example, if all the sunlight were absorbed high in the atmosphere and none reached the ground, and if the surface could radiate energy to space without hindrance, the surface temperature would fall to that of an airless planet. If the absorption of solar energy were to take place above most of the atmosphere, the earth's radiation budget would be balanced without the greenhouse effect. (Accordingly we refer to this condition as the "anti-greenhouse effect.") Below the layer where the sunlight was absorbed the temperature of the atmosphere would not vary with altitude: at each lower level the upward infrared flux would equal the downward infrared flux and the net energy transfer would be negligible.

Particles in the atmosphere can affect the earth's radiation balance in several ways: by absorbing sunlight, by reflecting sunlight back into space and by absorbing or emitting infrared radiation. In general a cloud of fine particles—an aerosol—tends to warm the atmospheric layer it occupies, but it can either warm or cool the underlying layers and the surface, depending on whether the particles absorb infrared radiation more readily than they reflect and/or absorb visible light.

The anti-greenhouse effect of an aerosol is maximized for particles that are highly absorbing at visible wavelengths. Thus much less sunlight reaches the surface when an aerosol consists of dark particles such as soot, which strongly absorb visible light, than when an aerosol consists of bright particles such as soil dust, which mainly scatter the light. Consequently in evaluating the possible climatic effects of a nuclear war particular concern should be focused on the soot particles that are generated by fires, since soot is one of the few common particulate materials that absorb visible light much more strongly than they absorb infrared radiation.

How much an aerosol will cool the surface (by blocking sunlight) or warm the surface (by enhancing the greenhouse effect) depends on the size of the particles. If the average diameter of the particles is less than a typical infrared wavelength (about 10 micrometers), the infrared opacity of the aerosol will be less than its visible opacity. Accordingly an aerosol of very fine particles that even weakly absorb sunlight should have a visible effect greater than its infrared effect, giving rise to a significant cooling of the lower atmospheric layers and the surface. In the case of soot this is true even for somewhat larger particles.

The visible and infrared radiation effects associated with particle layers also depend on the thickness and density of the aerosol. The intensity of the sunlight reaching the ground decreases exponentially with the quantity of fine, absorbing particulate matter in the atmosphere. The infrared radiation reaching the ground, however, depends more on the air temperature than it does on the quantity of aerosol. Hence when a large amount of aerosol is present, the dominant climatic consequence tends to be strong surface cooling.

The "optical depth" of an aerosol (a measure of opacity equal to the negative natural logarithm of the attenuation of an incident light beam by absorption and scattering) serves as a convenient indicator of the aerosol's potential climatic effects. For example, a cloud with an optical depth of much less than 1

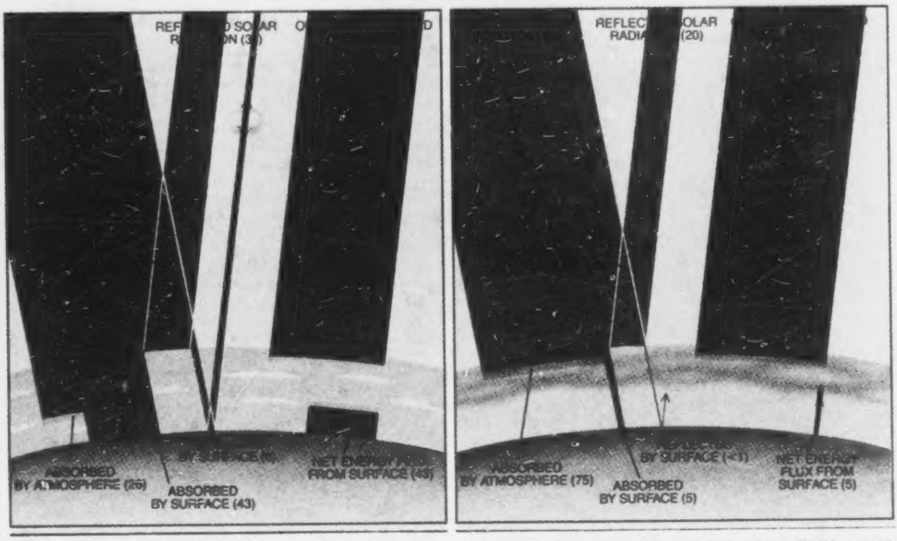
FIRESTORM DEVELOPS in the aftermath of a one-megaton nuclear explosion over the heart of New York in the hypothetical sequence of events depicted on the opposite page. (The skyline of the city, viewed here from the west, is drawn to scale; the detonation point is assumed to be at a height of 6,500 feet directly over the Empire State Building.) In the first few seconds after the detonation the initial flash of thermal radiation from the fireball would spontaneously ignite fires in combustible materials at a considerable distance (*1*). Many of these fires would be promptly snuffed out by the passage of the spherical blast wave (*black arcs*) and the accompanying high winds, but those two effects would also start a large number of secondary fires in the process of destroying most of the city's structures (*2*). Some of the individual primary and secondary fires could then merge into major conflagrations (*3*), which in turn might coalesce into a single massive fire covering most of the city (*4*). If such a fire were intense enough and the meteorological conditions were favorable, a full-scale firestorm could ensue, driven by winds of 100 miles per hour or more in the vicinity of the central updraft (*5*). Eventually the fire would burn itself out, leaving a smoldering residue (*6*). The smoke and dust thrown up by thousands of such explosions could extend over a large region, effectively blocking the sunlight and drastically reducing the surface temperature, regardless of the season. In the authors' "base line" 5,000-megaton nuclear-war scenario little soot is injected into the stratosphere by urban firestorms; if such firestorms were common in a nuclear war, the resulting nuclear winter would be much severer than the one predicted by the computer models.

would cause only minor perturbations, since most of the light would reach the surface, whereas a cloud with an optical depth of 1 or more would cause a major disturbance, since most of the light would be absorbed in the atmosphere and/or scattered away into space. Although volcanic particles happen to have an optimal size for enhancing visible effects over infrared effects, the magnitude of the induced surface cooling is limited by the modest optical depth of volcanic aerosols (less than about .3) and by their very weak intrinsic absorption at visible wavelengths. Nevertheless, the largest volcanic clouds may disturb the earth's radiation balance enough to cause anomalous weather. Much more significant climatic disturbances could result from the huge clouds of dust that would be thrown into the atmosphere by the impact of an asteroid or a comet with a diameter of several kilometers or more. These dust clouds could have a very large optical depth, perhaps initially as high as 1,000.

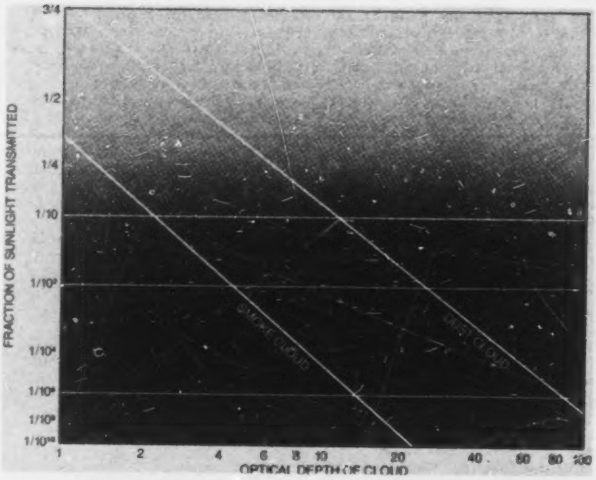
The radiative effects of an aerosol on the temperature of a planet depend not only on the aerosol's optical depth, its visible absorptivity and the average size of its particles but also on the variation of these properties with time. The longer a significant optical depth can be sustained, the closer the surface temperature and the atmospheric temperature will move toward a new state of equilibrium. Normally it takes the surface of the ocean several years to respond to changes in the global radiation balance, because of the great heat capacity of the mixed uppermost layer of the ocean, which extends to a depth of about 100 meters. In contrast, the air temperature and the continental land temperature approach new equilibrium values in only a few months. In fact, when the atmosphere is strongly cooled, convection above the surface ceases and the ground temperature falls rapidly by radiative cooling, reaching equilibrium in a few days or weeks. This happens naturally every night, although equilibrium is not reached in such a short period.

Particles are removed from the atmosphere by several processes: falling under the influence of gravity, sticking to the ground and other surfaces and scavenging by water clouds, rain and snow. The lifetime of particles against "wet" removal depends on the frequency of cloud formation and precipitation at various altitudes. In the first few kilometers of altitude in the normal atmosphere particles may in some places be washed out in a matter of days. In the upper troposphere (above five kilometers) the average lifetime of the particles increases to several weeks or more. Still higher, in the stratosphere (above 12 kilometers), water clouds rarely form and so the lifetime of small particles is typically a year or more. Stratospheric removal is primarily by gravitational settling and the large-scale convective transport of the particles. The deposition of particles on surfaces is very inefficient for average-size smoke and dust particles, requiring several months for significant depletion.

Clearly the height at which particles are injected into the atmosphere af-


ABSORBED BY ATMOSPHERE (26)
ABSORBED BY SURFACE (43)
NET ENERGY FROM SURFACE (43)
REFLEC OLAR RADIA (20)
ABSORBED BY ATMOSPHERE (75)
ABSORBED BY SURFACE (5)
BY SURFACE (<1)
NET ENERGY FLUX FROM SURFACE (5)

"GREENHOUSE EFFECT," the phenomenon whereby the earth's surface is warmed by the insulating properties of the atmosphere, could be negated over a large area by the cloud of smoke and dust resulting from a nuclear war. Under normal conditions (*left*) the atmosphere is quite transparent to radiation at visible wavelengths; accordingly a large fraction of the incident sunlight passes through the atmosphere and is absorbed by the surface in the form of thermal energy, or heat. Thermal radiation from the surface is emitted predominantly at longer, infrared wavelengths, which are strongly absorbed by the lower atmosphere, raising the temperature near the surface to levels well above the freezing point of water. Under normal conditions the net heat balance at the ground is the difference between a downward infrared flux of 101 units and an upward energy flux of 144 units; the latter value in turn consists of an upward infrared flux of 115 units plus an upward flux of latent and "sensible" heat totaling 29 units. The energy absorbed by the atmosphere and the surface in the form of sunlight, averaged over time, is equal to the energy emitted back into space from the surface and the atmosphere in the form of infrared radiation. A dense cloud of smoke and dust in the upper or middle atmosphere would rebalance the earth's energy budget (*right*). Most of the sunlight would then be absorbed by the cloud, and a large fraction would be reradiated directly back into space at infrared wavelengths without ever reaching the surface. Under these perturbed conditions the net heat balance at the ground would be the difference between a downward infrared flux of 65 units and an upward infrared flux of 70 units; the two fluxes would almost balance, canceling any heating effect in the atmosphere. The surface and the lower atmosphere would cool rapidly as the residual heat dissipated.



TRANSMISSION OF SUNLIGHT through smoke clouds and dust clouds is represented in this graph as a function of each cloud's optical depth, a measure of opacity equal to the negative natural logarithm of the attenuation of an incident light beam. At a given optical depth a smoke cloud evidently absorbs much more sunlight than a dust cloud. Three typical levels of transmitted light are given for comparison: they correspond to a very cloudy day (*a*), a light level at which photosynthesis is barely possible (*b*) and a clear night with a full moon (*c*).

cts their residence time. In general, e higher the initial altitude, the longer e residence time in the normal atmos- here. Massive injections of soot and ust, however, may profoundly alter oth the structure of the atmosphere nd the rate of particle removal.

In our analysis of the climatic effects f nuclear war we have adopted a num- er of specific scenarios, based on what s publicly known about the effects of individual nuclear explosions, the size and deployment of the world's present nuclear arsenals and the nuclear-war-fighting plans of the U.S. and the U.S.S.R. Among the several dozen cases we have analyzed are a 100-megaton "countervalue" attack directed strictly against cities, a 3,000-megaton "counterforce" attack directed strictly against missile silos and a 10,000-megaton "full-scale exchange" directed against an assortment of targets on both sides. Our "base line" case is a 5,000-megaton nuclear exchange, with about 20 percent of the total explosive yield detonated over urban, suburban and industrial areas. All the postulated attack scenarios are well within the present capabilities of the two superpowers.

A nuclear explosion can readily ignite fires in either an urban or a rural setting. The flash of thermal radiation from the nuclear explosion, which has a spectrum similar to that of sunlight, accounts for about a third of the total energy yield of the explosion. The flash is so intense that a variety of combustible materials are ignited spontaneously at ranges of 10 kilometers or more from a one-megaton air burst detonated at a nominal altitude of a kilometer. The blast wave from the explosion would extinguish many of the initial fires, but it would also start numerous secondary fires by disrupting open flames, rupturing gas lines and fuel storage tanks and causing electrical and mechanical sparks. The destruction resulting from the blast wave would also hamper effective fire fighting and so promote the spread of both the primary and the secondary fires. Based on the known incendiary effects of the nuclear explosions over Hiroshima and Nagasaki in 1945 it can be projected that the fires likely to be caused by just one of the far more powerful strategic nuclear weapons available today would extend over an area of from tens to hundreds of square kilometers.

Nuclear explosions over forests and grasslands could also ignite large fires, but this situation is more difficult to evaluate. Among the factors that affect fires in wilderness areas are the humidity, the moisture content of the fuel, the amount of the fuel and the velocity of the wind. Roughly a third of the land area in the North Temperate Zone is covered by forest, and an equal area is covered by brush and grassland. Violent wildfires have been known to spread over tens of thousands of square kilometers from a few ignition points; in the absence of a nuclear war such fires occur about once every decade. Although most wildfires generated by nuclear explosions would probably be confined to the immediate area exposed to the intense thermal flash, it is possible that much larger ones would be started by multiple explosions over scattered military targets such as missile silos.

The total amount of smoke likely to be generated by a nuclear war depends on, among other things, the total yield of the nuclear weapons exploded over each type of target, the efficiency of the explosions in igniting fires, the average area ignited per megaton of yield, the average amount of combustible material in the irradiated region, the fraction of the combustible material consumed by the fires, the ratio of the amount of smoke produced to the amount of fuel burned and the fraction of the smoke that is eventually entrained into the global atmospheric circulation after local rainfall has removed its share. By assigning the most likely values to these parameters for a nuclear war involving less than 40 percent of the strategic arsenals of the two superpowers we were able to calculate that the total smoke emission from a full-scale nuclear exchange could easily exceed 100 million metric tons. In many respects this is a conservative estimate. Crutzen and his co-workers Ian Galbally of the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia and Christoph Brühl of the Max Planck Institute at Mainz have recently estimated that the total smoke emission from a full-scale nuclear war would be closer to 300 million tons.

One hundred million tons of smoke, if it were distributed as a uniform cloud over the entire globe, could reduce the intensity of sunlight reaching the ground by as much as 95 percent. The initial clouds would not cover the entire globe, however, and so large areas of the Northern Hemisphere, particularly in the target zones, would be even darker; at noon the light level in these areas could be as low as that of a moonlit night. Daytime darkness in this range, if it persisted for weeks or months, would trigger a climatic catastrophe. Indeed, significant disturbances might be caused by much smaller amounts of smoke.

Wildfires normally inject smoke into the lower atmosphere to an altitude of five or six kilometers. In contrast, large urban fires have been known to inject smoke into the upper troposphere, probably as high as 12 kilometers. The unprecedented scale of the fires likely to be ignited by large nuclear explosions and the complex convective activity generated by multiple explosions might cause some of the smoke to rise even higher. Studies of the dynamics of very large fires suggest that individual smoke plumes might reach as high as 20 kilometers, well into the stratosphere.

During the World War II bombing of Hamburg the center of the city was gutted by an intense firestorm, with heat-generated winds of hurricane force sweeping inward from all directions at ground level. Rapid heat release over a large area can create fire vortexes, heat tornadoes and cyclones with towering convective columns. The sheer intensity of such fires might act to reduce the smoke emission considerably through two processes: the oxidation of carbonaceous smoke particles at the extremely high temperatures generated in the fire zone and the washout of smoke particles by precipitation formed in the convective column. Both effects were taken into account in our estimates of the total smoke emission from a nuclear war.

The climatic impact of smoke depends on its optical properties, which in turn are sensitive to the size, shape and composition of the smoke particles. The most effective light-screening smoke consists of particles with a radius of about .1 micrometer and a very sooty composition rich in graphite. The least effective smoke in attenuating sunlight consists of particles larger than .5 micrometer with a predominantly oily composition. The smoke from a forest fire is typically composed of extremely fine oily particles, whereas the smoke from an urban fire consists of larger agglomerations of sooty particles. Smoke from fierce fires usually contains large particles of ash, char, dust and other debris, which is swept up by the heat-generated winds. The largest of these particles fall out of the smoke clouds just downwind of the fire. Although very intense fires produce less smoke, they lift more fine dust and may burn metals such as aluminum and chromium, which efficiently generate fine aerosols.

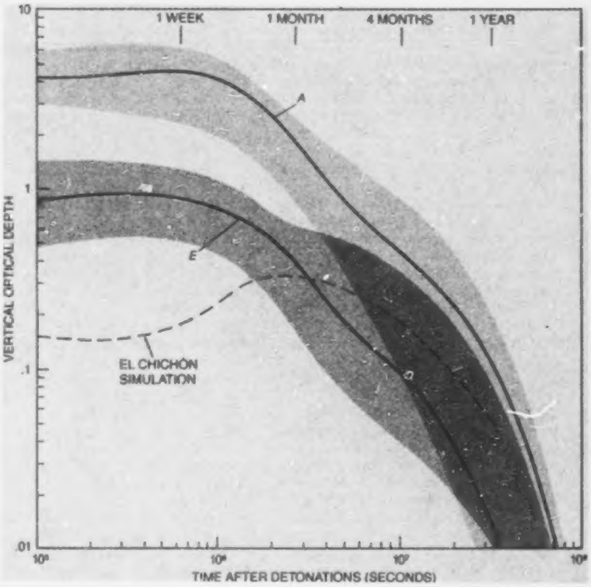
The release of toxic compounds in urban fires has not been adequately studied. It is well known that many people who have died in accidental fires have been poisoned by toxic gases. In addition to carbon monoxide, which is produced copiously in many fires, hydrogen cyanide and hydrogen chloride are generated when the synthetic compounds in modern building materials and furnishings burn. If large stores of organic chemicals are released and burned in a nuclear conflict, additional airborne toxins would be generated. The possibility that vast areas could be contaminated by such pyrotoxins, adsorbed on the surface of smoke, ash and dust particles and carried great distances by winds, needs further investigation.

Nuclear explosions at or near ground level throw up huge amounts of dust. The principal dust-forming mechanisms include the ejection and disaggregation of soil particles from the crater formed by the explosion; the vaporization and subsequent renucleation of soil and rock, and the lifting of surface dust and smoke. A one-megaton explosion on land can excavate a crater hundreds of meters in diameter, eject several million tons of debris, lift between 100,000 and 600,000 tons of soil to a high altitude and inject between 10,000 and 30,000 tons of submicrometer dust particles into the stratosphere. The height at which the dust is injected depends on the yield of the explosion: the dust clouds produced by explosions with a yield of less than about 100 kilotons will generally not penetrate into the stratosphere, whereas those from explosions with a yield of more than about a megaton will stabilize mainly within the stratosphere. Explosions above the ground can also raise large quantities of dust, which is vacuumed off the surface by the rising fireball. The combined effects of multiple explosions could enhance the total amount of dust raised to high altitudes.

The quantity of dust produced in a nuclear war would depend sensitively on the way the weapons were used. Ground bursts would be directed at hard targets, such as missile silos and underground command posts. Soft targets could be attacked by air bursts as well as ground bursts. There are more than 1,000 missile silos in the continental U.S. alone, and at least two Russian warheads are probably committed to each of them. Some 1,400 missile silos in the U.S.S.R. are similarly targeted by U.S. warheads. Air bases and secondary airfields, submarine pens and command and control facilities are among the many other strategic targets to which ground bursts might be assigned. In short, it seems quite possible that at least 4,000 megatons of high-yield weapons might be detonated at or near ground level even in a war in which cities were not targeted, and that roughly 120 million tons of submicrometer soil particles could be injected into the stratosphere in the North Temperate Zone. This is many times greater than all the submicrometer dust lifted into the stratosphere by the eruption of the volcano El Chichón in Mexico in 1982 and is comparable to the global submicrometer dust injections of much larger volcanic eruptions such as that of Tambora in 1815 and Krakatau in 1883.

	SCENARIO	TOTAL YIELD (MEGATONS)	SURFACE BURSTS (PERCENTAGE OF YIELD)	URBAN OR INDUSTRIAL TARGETS (PERCENTAGE OF YIELD)	YIELD OF WARHEADS (MEGATONS)	TOTAL NUMBER OF EXPLOSIONS	MASS OF SUBMICROMETER SMOKE (MILLIONS OF METRIC TONS)	MASS OF SUBMICROMETER DUST (MILLIONS OF METRIC TONS)	OPTICAL DEPTH OF SMOKE	OPTICAL DEPTH OF DUST
A	BASE-LINE EXCHANGE	5,000	57	20	.1–10	10,400	225	65	4.5	1
B	LOW-YIELD AIRBURSTS	5,000	10	33	.1–1	22,500	300	15	6	.2
C	FULL-SCALE EXCHANGE	10,000	63	15	.1–10	16,160	300	130	6	2
D	MEDIUM-SCALE EXCHANGE	3,000	50	25	.3–5	5,433	175	40	3.5	.6
E	LIMITED EXCHANGE	1,000	50	25	.2–1	2,250	50	10	1	.1
F	GENERAL COUNTERFORCE ATTACK	3,000	70	0	1–10	2,150	0	55	0	.8
G	HARD-TARGET COUNTERFORCE ATTACK	5,000	100	0	5–10	700	0	650	0	10
H	CITY ATTACK	100	0	100	.1	1,000	150	0	3	0
I	FUTURE WAR	25,000	72	10	.1–10	28,300	400	325	8	5

NUCLEAR-WAR SCENARIOS outlined in this table were drawn from a much longer list of possibilities considered in detail by the authors in their original study. The last four columns at the right give the outcome of each scenario in terms of the resulting clouds of smoke and dust. All the scenarios shown here except the last one are thought to be well within the present capabilities of the two superpowers.



VARIATION IN OPACITY OVER TIME of the clouds of smoke and dust resulting from a number of nuclear-war scenarios is traced here in terms of the clouds' vertical optical depth averaged over the Northern Hemisphere. The optical depths were calculated for visible light at a wavelength of 550 nanometers. The results tend to fall into two bands. The upper band includes those scenarios that gave results close to the authors' 5,000-megaton base-line case, indicated by the solid-color curve; the total explosive yields of the scenarios in this band range from 100 to 10,000 megatons. The lower band includes those scenarios that gave less drastic results; the scenarios in this band range from the 1,000-megaton limited exchange indicated by the black curve to a 3,000-megaton counterforce attack aimed at military targets only. Significant climatic disruptions are expected whenever the average optical depth over a hemisphere is greater than about 1. The average optical depth over the Northern Hemisphere of the cloud of dust raised by the eruption of the volcano El Chichón in 1982 is given for comparison.

Analogies between the atmospheric effects of a major volcanic explosion and a nuclear war are often made for convenience. Nevertheless, there is no straightforward way to scale the effects of a volcanic explosion against those of a series of nuclear detonations. The aerosol particles produced by volcanoes are fundamentally different in composition, size and shape from those produced by nuclear explosions. We have therefore based our calculations on the properties of dust measured directly in nuclear-explosion clouds.

The only proper comparison between a volcanic eruption and a nuclear explosion is the optical depth of the long-term aerosols that are produced. In fact, we utilized data on global "dust veils" generated by volcanic explosions to test and calibrate our climate models. In so doing we have been able to account quantitatively for the hemispheric surface-cooling effect observed after major volcanic eruptions. The present nuclear-dust calculations are entirely consistent with observations of volcanic phenomena. For example, it is now clear that violent eruptions can lead to a significant climatic cooling for a year or more. Even so, in recorded history volcanoes have had only a rather modest climatic role. The fact that volcanoes are localized sources of dust limits their geographic influence; moreover, volcanoes inject comparatively little fine dust (and no soot) into the stratosphere. Nuclear explosions, on the other hand, are a powerful and efficient means of injecting large quantities of fine soot and dust into the atmosphere over large regions.

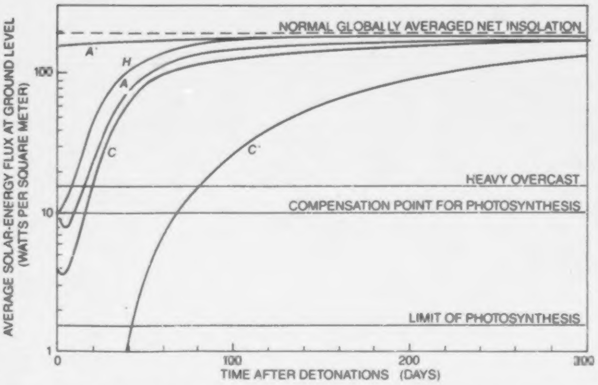
The atoms produced in the fission reactions of a nuclear explosion are often in unstable isotopic states. Radioactive decay from these states releases alpha, beta and gamma radiation. In most nuclear weapons at least half of the energy yield is generated by fission and the rest by fusion. About 300 distinct radioactive isotopes are produced. Most of them condense onto aerosols and dust formed in (or sucked into) the fireball. Accordingly the dust and the radioactivity generated by nuclear explosions are intimately related.

Of particular interest here are the prompt and the intermediate radioactive fallout. The former is associated with short-lived radioactive isotopes that condense onto large soil particles, which in turn fall to the ground within hours after an explosion. Intermediate fallout is associated with longer-lived radioactive isotopes carried by smaller particles that drift in the wind and are removed by settling and precipitation in the interval from days to months. Prompt fallout is generated by ground bursts, and intermediate fallout is generated by ground bursts and air bursts in the yield range from 10 to 500 kilotons, which deposit their radioactivity in the middle and upper troposphere.

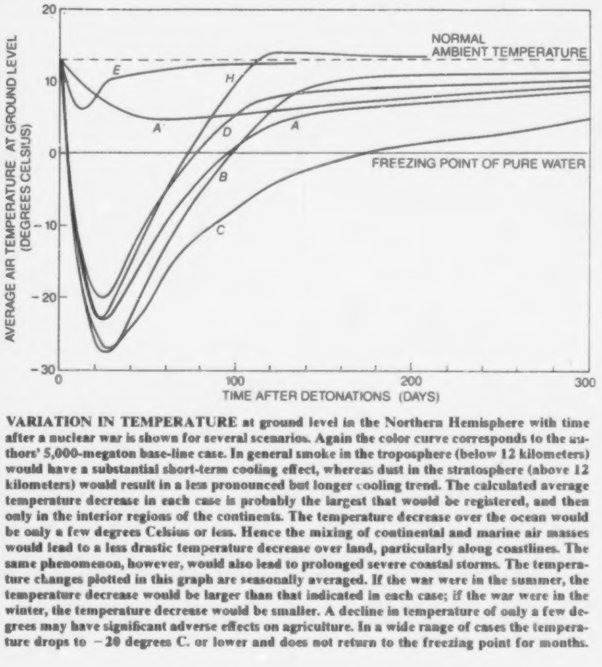
The danger from radioactive fallout is measured in terms of the total dose in rads (a unit of radiation exposure equivalent to 100 ergs of ionizing energy deposited in one gram of tissue), the dose rate in rads per hour and the type of radiation. The most deadly effects are caused by the intense, penetrating gamma radiation from prompt fallout. The widespread intermediate fallout delivers a less potent long-term gamma-ray dose. A whole-body gamma-ray exposure of 450 rads, received over several days, is lethal to half of the healthy adults exposed. Chronic doses of 100 rads or more from intermediate fallout could suppress the immune system even of healthy people and would cause long-term increments in the incidence of cancer, genetic defects and other diseases.

Our most recent studies of the effects of radioactive fallout in our base-line case indicate that the prompt fallout could contaminate millions of square kilometers of land with lethal radioactivity. The intermediate fallout would blanket at least the North Temperate Zone, producing average long-term, whole-body gamma-ray exposures of about 50 rads in unprotected populations. Internal exposures of specific organs to biologically active radioactive isotopes such as strontium 90 and iodine 131, which enter the food chain, could double or triple the total doses. According to Joseph B. Knox of the Lawrence Livermore National Laboratory, if nuclear power plants were targeted directly, the average long-term gamma-ray dose could be increased to several hundred rads or more.

The computer models we have employed to define the potential magnitude of the long-term global aftereffects of nuclear war are one-dimensional: they treat only the vertical structure of the atmosphere. Obviously the atmosphere is a complex three-dimensional system



VARIATION IN THE AMOUNT OF SUNLIGHT reaching the ground through a widely dispersed cloud of smoke and dust created by a nuclear war is shown for several of the nuclear-war scenarios considered by the authors. Each curve gives the average solar-energy flux at the ground in the Northern Hemisphere for a given scenario. The fluxes correspond to horizontally averaged smoke clouds and do not take into account possible patchiness in the clouds. The color curve corresponds to the 5,000-megaton base-line case (*curve A*). Curve *A'* is a variant of the base-line case that takes into account only the effects of dust. Curve *C'* is a variant of the 10,000-megaton full-scale exchange that assigns more extreme values to the smoke-emission parameters. Also indicated are the energy level at which photosynthesis cannot keep pace with the respiration of a typical plant (a level known as the compensation point) and the energy level at which photosynthesis ceases. These two thresholds vary considerably from plant to plant.



VARIATION IN TEMPERATURE at ground level in the Northern Hemisphere with time after a nuclear war is shown for several scenarios. Again the color curve corresponds to the authors' 5,000-megaton base-line case. In general smoke in the troposphere (below 12 kilometers) would have a substantial short-term cooling effect, whereas dust in the stratosphere (above 12 kilometers) would result in a less pronounced but longer cooling trend. The calculated average temperature decrease in each case is probably the largest that would be registered, and then only in the interior regions of the continents. The temperature decrease over the ocean would be only a few degrees Celsius or less. Hence the mixing of continental and marine air masses would lead to a less drastic temperature decrease over land, particularly along coastlines. The same phenomenon, however, would also lead to prolonged severe coastal storms. The temperature changes plotted in this graph are seasonally averaged. If the war were in the summer, the temperature decrease would be larger than that indicated in each case; if the war were in the winter, the temperature decrease would be smaller. A decline in temperature of only a few degrees may have significant adverse effects on agriculture. In a wide range of cases the temperature drops to −20 degrees C. or lower and does not return to the freezing point for months.

whose intricate interactions determine its response to perturbations. At present, however, there are no three-dimensional models with the appropriate features to treat the nuclear-winter problem with high precision, although several such models are under development. The existing models of the climate and the general circulation of the atmosphere incorporate a number of empirical approaches to physical processes that are not well understood. In the nuclear-winter scenario the climate is so seriously perturbed that such treatments are of dubious applicability.

Our approach has therefore been to estimate the first-order effects through detailed microphysical, chemical and optical calculations in a one-dimensional format. Even this simplified approach had not been attempted before our work, and it was not clear then that more sophisticated three-dimensional work was justified. Based on the predicted first-order one-dimensional effects, the principal three-dimensional meteorological interactions that would have to be treated in more refined studies were deduced. The three-dimensional results generally confirm our one-dimensional results.

Three basic models were used in our study: a nuclear-scenario model, a particle-microphysics model and a radiative-convective climate model. The nuclear-scenario model determines the quantities of smoke, dust, radioactivity and pyrotoxins generated by a specific nuclear exchange, relying on (among other things) the smoke and dust estimates cited above. The microphysics model simulates the evolution of the quantity and the size of the smoke and dust particles and the deposition of radioactivity by accounting for the physical interactions and vertical transport of particles at all altitudes. The radiative-convective model calculates the optical and infrared properties of the evolving particles, the visible and infrared energy fluxes and air temperatures as a function of time and altitude. Because the predicted air temperatures are sensitive to surface heat capacities, separate calculations were done for land and ocean environments to define possible temperature differences.

One-dimensional models cannot accurately forecast the short-term or local effects of a nuclear war. The applicability of the predictions based on such models depends on the rate and extent of the dispersion of the smoke plumes and dust clouds. Soon after a nuclear exchange thousands of individual smoke and dust clouds would be distributed throughout the North Temperate Zone at altitudes of up to 20 kilometers. The action of horizontal turbulent diffusion, vertical wind shear and continuing smoke emission would almost certainly spread the clouds of nuclear debris over the entire zone and fill in gaps in the clouds within a week. Local effects in this period could vary considerably from the average effects simulated with our one-dimensional models.

Since large uncertainties are inherent in any assessment of the effects of nuclear warfare, a variety of simulations were made to investigate the sensitivity of various outcomes to changes in scenarios and in key physical parameters. Although all these results cannot be discussed in an article of this length, some selected findings are summarized in the illustrations accompanying this article.

In general our results suggest that the optical depth of the cloud of smoke and dust resulting from a massive nuclear exchange would at the very least be comparable to or larger than that of the cloud resulting from a major volcanic eruption, and that the most probable optical depth would be an order of magnitude larger. The likeliest outcome of a nuclear war would therefore be a climatic catastrophe.

The ultimate impact of smoke and dust on climate depends on the fraction of sunlight they screen from the surface. This suggests that a saturation effect will occur. For example, a smoke cloud with an optical depth of 3 can prevent 95 percent or more of the sunlight from reaching the ground. Greater optical depths cause only negligible further decreases in the average surface sunlight. Thus an average optical depth of about 3 is roughly the saturation level for smoke-induced climatic effects. The saturation level for dust occurs at an optical depth of about 20, and its onset is much more gradual with increasing optical depth than the saturation level for smoke. It is doubtful whether enough dust could be raised in a nuclear war to create optical saturation on a global scale.

How a smoke cloud extinguishes light also differs from how a dust cloud does so. A sooty pall of smoke absorbs most of the incident light and scatters only a small fraction back into space or down toward the surface. The absorption rapidly heats the smoke clouds, inducing powerful air motions and winds. Dust clouds, on the other hand, primarily scatter the incident sunlight and absorb only a small fraction. To block light effectively clouds that are purely light-scattering must be very thick, because much of the light is scattered forward toward the earth's surface; for example, ordinary water clouds typically have an optical depth of 10 or more.

We find that for many scenarios a substantial reduction in sunlight may persist for weeks or months after the war. In the first week or two the clouds would also be patchy; hence our calculations probably underestimate the average light intensity at these early stages. Nevertheless, within the target zones it would be too dark to see, even at noon.

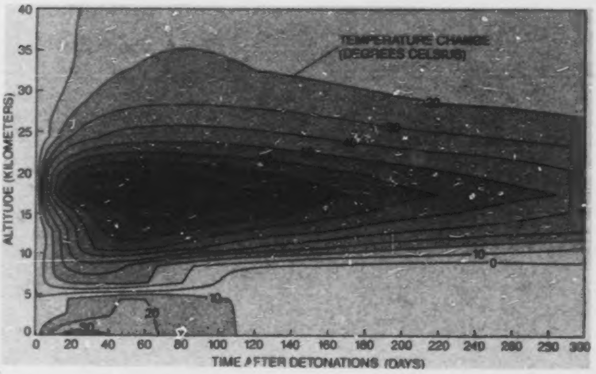
The large amount of smoke generated by a nuclear exchange could lead to dramatic decreases in continental temperatures for a substantial period. In many of the scenarios represented in the illustrations accompanying this article land temperatures remain below freezing for months. Average temperature decreases of only a few degrees Celsius in spring or early summer could destroy crops throughout the North Temperate Zone. Temperature drops of some 40 degrees C. (to an absolute temperature of about −25 degrees C.) are predicted for the base-line case, and still severer cooling effects are possible with the current nuclear arsenals and with those projected for the near future.

The predicted changes in air temperature as a function of height and time for our 5,000-megaton base-line scenario reveal several important features. First, the upper atmosphere is heated by between 30 and 80 degrees C. as the sunlight, which normally warms the ground, is absorbed in the highest smoke layers. At the same time the ground cools in darkness. The hot clouds, like hot-air balloons, would not remain stationary but would rise and expand.

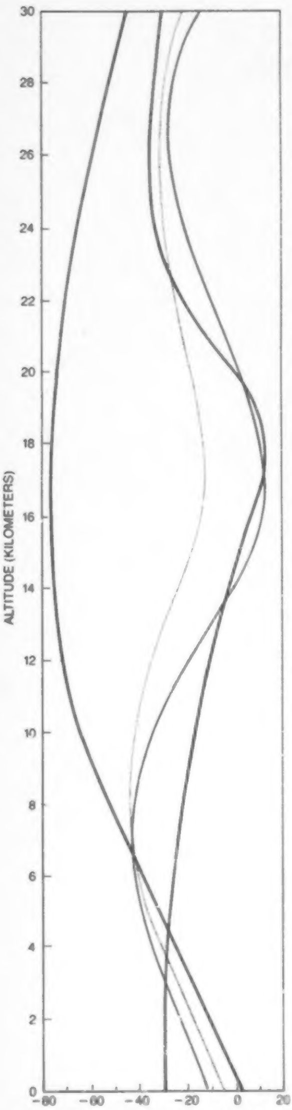
A month after a massive nuclear exchange the entire troposphere over land could be thermally brought to a standstill. Even after three months only the lowest few kilometers would receive enough solar energy to drive weak convection. In effect the stratosphere would descend to the surface, creating an alien atmosphere. In some places warm currents of ocean air would still sweep into the continents at ground level, but this heat source would be able to drive convection only within the lowest few kilometers of the atmosphere. The intense temperature inversion would effectively damp deep convective activity. Elsewhere cold air flowing off the continents might warm over the oceans, rise and recirculate over the continents and finally subside over the land.

One possible consequence of the temperature inversion caused by such a smoke cloud would be an increase in the atmospheric residence time of the smoke and dust. This outcome represents a positive feedback effect, not taken into account in any calculations so far, that would increase both the severity and the duration of the nuclear winter. The temperature inversion reduces the convective penetration of moist air from below, inhibiting the condensation of water in the sooty air and hence greatly limiting precipitation at altitudes higher than a few kilometers. The longer soot and dust remain in the atmosphere, the farther they spread horizontally and the more widespread their climatic impact is. Under these conditions the particles are removed mainly by continuing coagulation and fallout and by transport in global-scale wind systems and turbulence to low altitudes where precipitation scavenging still takes place.

Our calculated temperature changes over extended land masses do not account for the initial patchiness in the clouds or the later dilution of cold continental air by warm marine air. Michael C. MacCracken of Livermore has investigated the combined effects of patchi-



VARIATION IN TEMPERATURE WITH ALTITUDE over the northern continents is plotted in this contour diagram for the first year after the 5,000-megaton base-line nuclear war. The contours give the average change in temperature at intervals of 10 degrees C., based on the authors' one-dimensional radiative-convective model. The gray area indicates parts of the atmosphere that are cooled below their normal temperature; the color area indicates parts that are heated above their normal temperature. The strong heating effect in the upper troposphere and lower stratosphere is attributable mainly to the absorption of sunlight by smoke and dust.



TEMPERATURE PROFILES of the atmosphere before and after a 5,000-megaton nuclear war are compared. The black curve is the normal temperature profile. The other curves show the profile one month after the war (*dark color*), three months after (*medium color*) and six months after (*light color*).

ness in clouds and the transfer of heat from the ocean, working with a general-circulation model to trace large blobs of smoke; he has also worked with a two-dimensional climate model to calculate land temperatures corresponding to the smoke emission in our 5,000-megaton base-line scenario. He finds average temperature decreases on land that are roughly half our continental-interior temperature drops. Even more sophisticated three-dimensional general-circulation-model calculations for conditions similar to our base-line scenario confirm that temperature drops of between 20 and 40 degrees C. are possible over vast continental areas.

The results of our computations indicate that the motions induced in soot clouds by the absorption of sunlight might cause the soot cloud to rise and spread out horizontally. This phenomenon could accelerate both the early dispersal and the global spreading of smoke plumes, a process that is otherwise dominated by wind shear and turbulence. Recently a group at the National Aeronautics and Space Administration's Ames Research Center, consisting of Robert M. Haberle and two of us (Ackerman and Toon), applied an advanced two-dimensional global-circulation model to compute the motion of heated soot clouds in the earth's troposphere. The Ames group considered a uniform soot cloud between 30 and 60 degrees north latitude, encircling the earth at these latitudes and extending from the ground to an altitude of eight kilometers. This smoke simulation shows massive fragments of the cloud rising high into the stratosphere and moving briskly toward the Equator and the Southern Hemisphere.

Although these calculations are preliminary, they support a major hypothesis of our initial study: that self-propelled smoke and dust clouds from the Northern Hemisphere could be rapidly transported to the Southern Hemisphere, causing large climatic anomalies there as well. Such accelerated dispersal could have the most severe consequences in the Tropics of both hemispheres, where the indigenous organisms are extremely sensitive to dark and cold. A nuclear winter extending to the Tropics would represent an ecological disaster unprecedented in history.

Our speculations about major meteorological disturbances and interhemispheric transport following a nuclear conflict have received further support from sophisticated calculations with three-dimensional models of global circulation. These models are not yet designed to move smoke and dust as tracer elements or to make the required detailed radiative-transport calculations. Nevertheless, they are able to define the initial three-dimensional perturbations in winds and temperatures caused by massive smoke injections. Two research groups have made these advanced climate studies: Curt Covey, Stephen H. Schneider and Starley L. Thompson of the National Center for Atmospheric Research (NCAR) in Boulder, Colo., and Vladimir V. Alexandrov and Georgi L. Stenchikov of the Computing Center of the Academy of Sciences of the U.S.S.R.

The predictions made by both groups of the normal and perturbed meridional, or north-south, circulation of the atmosphere several weeks after a nuclear exchange in the Northern Hemisphere in the spring or summer lead to the same conclusion: the normally bifurcated "Hadley cell" circulation in the Tropics would be transformed into a single intense cell with strong winds in the upper troposphere flowing directly from the Northern Hemisphere to the Southern Hemisphere. This would represent a profound change in the global wind system.

The average meridional circulation is the residual motion of large-scale planetary-wave oscillations. The global-circulation models predict anomalies in the planetary-wave motions, and here too the results are surprising. The NCAR group finds that continent-size bodies of heated air could penetrate deep into the Southern Hemisphere in a matter of days. Essentially all the habitable land masses of the earth could be subject to rapid blackout by soot. The global-circulation models also forecast subfreezing temperatures over most of the northern continental regions. What is startling is that local freezing could occur within two or three days; the NCAR group refers to it as a "quick freeze." Under such circumstances practically no area of the globe, north or south, would be safe from nuclear winter.

Consideration of the possible weather activity near coastlines during the nuclear winter suggests that even if the incident sunlight were reduced significantly, the oceans would continue to feed heat and moisture into the marine boundary layer near coastlines. In some regions cold offshore winds would interact with the marine environment to produce intense storms and heavy precipitation. In other regions, as prevailing winds swept ocean air onto cold continents, thick stratus clouds and continuous precipitation could ensue. It is not known how far this severe weather might extend inland from the coastlines, but a 100-kilometer margin would probably include most of the activity.

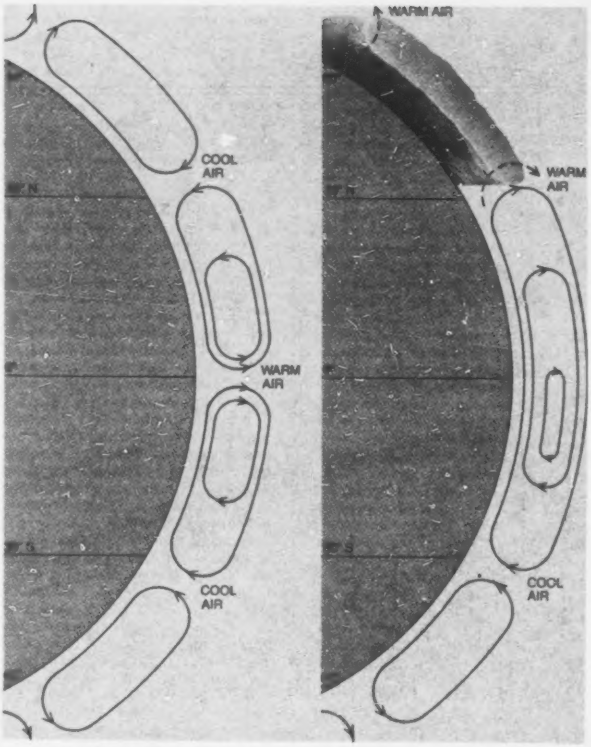
There are many additional questions about nuclear winter that remain to be answered. With rapid surface cooling widespread fogs would develop, and they might affect the radiation balance at the surface. The presence of millions of tons of nuclear debris in the atmosphere could modify the properties of cloud droplets and so the removal rate of the debris. The nuclear clouds and modified natural clouds would also affect the overall infrared-radiation balance of the atmosphere, but the implications for surface temperatures remain uncertain. Daily variations, which have not yet been treated in the climate models applied to the nuclear-war problem, could also influence the dynamics and removal of the nuclear debris. Water injected by nuclear explosions and fires might affect atmospheric chemical and radiative processes. All these effects are important second-order refinements of the basic climatic theory of the nuclear winter. On the basis of the existing scientific evidence, however, none of these effects appears to be capable of significantly altering the major climatic impacts now predicted for a nuclear war.

There is also a lack of understanding of the interactions of the atmosphere with the oceans, which may have a major influence on short-term climatic changes. Through what was perhaps a series of coincidences, the eruption of El Chichón in the spring of 1982 was followed by an unusually intense El Niño warming of the South Pacific in the winter of 1982 and spring of 1983, associated with an unexpected calming of the southerly trade winds. These events were followed by unusual weather in North America and Europe in the winter of 1982 and throughout 1983. Most of North America suffered record-breaking cold that winter, and Europe enjoyed a balmy spring in December. Although proof that these events were related is lacking, the evidence suggests a potentially significant coupling of ocean currents, winds and weather on a comparatively short time scale; such a relation has yet to be defined rigorously.

Our study also considered a number of secondary climatic effects of nuclear war. Changes in the albedo, or reflectivity, of the earth's surface can be caused by widespread fires, by the deposition of soot on snow and ice and by regional modifications of vegetation. Short-term changes in albedo were evaluated and found to be unimportant compared with the screening of sunlight. If significant semipermanent albedo changes were to occur, long-term climatic shifts could ensue. On the other hand, the vast oceanic heat source would act to force the climate toward contemporary norms following any major disturbance. Accordingly we have tentatively concluded that a nuclear war is not likely to be followed by an ice age.

We have also analyzed the climatic effects caused by changes in the gaseous composition of the atmosphere. The maximum hemispheric temperature perturbation associated with the production of oxides of nitrogen and the accompanying depletion of ozone is a cooling of no more than a few degrees C. The concentrations of greenhouse-effect gases would also be modified by a nuclear war; such gases might produce a surface warming of several degrees after the smoke and dust had cleared. These mutually offsetting temperature perturbations are uncertain, however, because the chemical and physical changes in the atmosphere caused by a nuclear war would be coupled through processes that are not adequately treated in existing models. Further analysis is clearly needed on this point.

Of course, the actual consequences of a nuclear war can never be precisely foreseen. Synergistic interactions among individual physical stresses might compound the problem of survival for many organisms. The long-term destruction of the environment and the disruption of the global ecosystem might in the end prove even more devastating for the human species than the awesome short-term destructive effects of nuclear explosions and their radioactive fallout. The strategic policies of both superpowers and their respective military alliances should be reassessed in this new light.



GLOBAL CIRCULATION PATTERN of the atmosphere could be disrupted by a major nuclear war in the Northern Hemisphere. In the spring and summer (in the Northern Hemisphere) the average global circulation in the meridional, or north-south, direction is dominated by the large convective feature called a Hadley cell, in which the air rises over the hot, humid Tropics, splits into two streams and descends over subtropical and middle latitudes in both hemispheres, establishing secondary circulation cells at higher latitudes (*diagram at left*). If a large, dense cloud of smoke and dust were to be introduced into the troposphere in the North Temperate Zone during these seasons, the tropospheric heating effect at the southern edge of the cloud might be intense enough to reverse the normal mid-latitude subsidence, converting the Hadley circulation into an unusual pattern characterized by a single dominant cell with upper-level winds blowing briskly across the Equator from north to south (*diagram at right*). This novel circulation pattern has been observed in sophisticated computer models of the general circulation of the atmosphere developed by investigators in the U.S. and the U.S.S.R.

23 December 1983, Volume 222, Number 4630 SCIENCE

Nuclear Winter: Global Consequences of Multiple Nuclear Explosions

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Summary. The potential global atmospheric and climatic consequences of nuclear war are investigated using models previously developed to study the effects of volcanic eruptions. Although the results are necessarily imprecise, due to a wide range of possible scenarios and uncertainty in physical parameters, the most probable first-order effects are serious. Significant hemispherical attenuation of the solar radiation flux and subfreezing land temperatures may be caused by fine dust raised in high-yield nuclear surface bursts and by smoke from city and forest fires ignited by airbursts of all yields. For many simulated exchanges of several thousand megatons, in which dust and smoke are generated and encircle the earth within 1 to 2 weeks, average light levels can be reduced to a few percent of ambient and land temperatures can reach −15° to −25°C. The yield threshold for major optical and climatic consequences may be very low: only about 100 megatons detonated over major urban centers can create average hemispheric smoke optical depths greater than 2 for weeks and, even in summer, subfreezing land temperatures for months. In a 5000-megaton war, at northern mid-latitude sites remote from targets, radioactive fallout on time scales of days to weeks can lead to chronic mean doses of up to 50 rads from external whole-body gamma-ray exposure, with a likely equal or greater internal dose from biologically active radionuclides. Large horizontal and vertical temperature gradients caused by absorption of sunlight in smoke and dust clouds may greatly accelerate transport of particles and radioactivity from the Northern Hemisphere to the Southern Hemisphere. When combined with the prompt destruction from nuclear blast, fires, and fallout and the later enhancement of solar ultraviolet radiation due to ozone depletion, long-term exposure to cold, dark, and radioactivity could pose a serious threat to human survivors and to other species.

Concern has been raised over the short- and long-term consequences of the dust, smoke, radioactivity, and toxic vapors that would be generated by a nuclear war (*1–7*). The discovery that dense clouds of soil particles may have played a major role in past mass extinctions of life on Earth (*8–10*) has encouraged the reconsideration of nuclear war effects. Also, Crutzen and Birks (*7*) recently suggested that massive fires ignited by nuclear explosions could generate quantities of sooty smoke that would attenuate sunlight and perturb the climate. These developments have led us to calculate, using new data and improved models, the potential global environmental effects of dust and smoke clouds (henceforth referred to as nuclear dust and nuclear smoke) generated in a nuclear war (*11*). We neglect the short-term effects of blast, fire, and radiation (*12–14*). Most of the world's population could probably survive the initial nuclear exchange and would inherit the postwar environment. Accordingly, the longer-term and global-scale aftereffects of nuclear war might prove to be as important as the immediate consequences of the war.

To study these phenomena, we used a series of physical models: a nuclear war scenario model, a particle microphysics model, and a radiative-convective model. The nuclear war scenario model specifies the altitude-dependent dust, smoke, radioactivity, and NO_x injections for each explosion in a nuclear exchange (assuming the size, number, and type of detonations, including heights of burst, geographic locales, and fission yield fractions). The source model parameterization is discussed below and in a more detailed report (*15*). The one-dimensional microphysical model (*15–17*) predicts the temporal evolution of dust and smoke clouds, which are taken to be rapidly and uniformly dispersed. The one-dimensional radiative-convective model (1-D RCM) uses the calculated dust and smoke particle size distributions and optical constants and Mie theory to calculate visible and infrared optical properties, light fluxes, and air temperatures as a function of time and height. Because the calculated air temperatures are sensitive to surface heat capacities, separate simulations are performed for land and ocean environments, to define possible temperature contrasts. The techniques used in our 1-D RCM calculations are well documented (*15, 18*).

Although the models we used can provide rough estimates of the average effects of widespread dust and smoke clouds, they cannot accurately forecast short-term or local effects. The applicability of our results depends on the rate and extent of dispersion of the explosion clouds and fire plumes. Soon after a large nuclear exchange, thousands of individual dust and smoke clouds would be distributed throughout the northern mid-latitudes and at altitudes up to 30 km.

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Horizontal turbulent diffusion, vertical wind shear, and continuing smoke emission could spread the clouds of nuclear debris over the entire zone, and tend to fill in any holes in the clouds, within 1 to 2 weeks. Spatially averaged simulations of this initial period of cloud spreading must be viewed with caution; effects would be smaller at some locations and larger at others, and would be highly variable with time at any given location.

The present results also do not reflect the strong coupling between atmospheric motions on all length scales and the modified atmospheric solar and infrared heating and cooling rates computed with the 1-D RCM. Global circulation patterns would almost certainly be altered in response to the large disturbances in the driving forces calculated here (*19*). Although the 1-D RCM can predict only horizontally, diurnally, and seasonally averaged conditions, it is capable of estimating the first-order climate responses of the atmosphere, which is our intention in this study.

Scenarios

A review of the world's nuclear arsenals (*20–24*) shows that the primary strategic and theater weapons amount to $\approx$ 12,000 megatons (MT) of yield carried by $\approx$ 17,000 warheads. These arsenals are roughly equivalent in explosive power to 1 million Hiroshima bombs. Although the total number of high-yield warheads is declining with time, about 7000 MT is still accounted for by warheads of > 1 MT. There are also $\approx$ 30,000 lower-yield tactical warheads and munitions which are ignored in this analysis. Scenarios for the possible use of nuclear weapons are complex and controversial. Historically, studies of the long-term effects of nuclear war have focused on a full-scale exchange in the range of 5000 to 10,000 MT (*2, 12, 20*). Such exchanges are possible, given the current arsenals and the unpredictable nature of warfare, particularly nuclear warfare, in which escalating massive exchanges could occur (*25*).

An outline of the scenarios adopted here is presented in Table 1. Our baseline scenario assumes an exchange of 5000 MT. Other cases span a range of total yield from 100 to 25,000 MT. Many high-priority military and industrial assets are located near or within urban zones (*26*). Accordingly, a modest fraction (15 to 30 percent) of the total yield is assigned to urban or industrial targets. Because of the large yields of strategic warheads [generally ≥ 100 kilotons (KT)], "surgical" strikes against individual targets are difficult; for instance, a 100-KT airburst can level and burn an area of ≈ 50 km^2, and a 1-MT airburst, ≈ 5 times that area (*27, 28*), implying widespread collateral damage in any "countervalue," and many "counterforce," detonations.

Table 1. Nuclear exchange scenarios.

Case*	Total yield (MT)	Percent of yield		Warhead yield range (MT)	Total number of explosions
		Surface bursts	Urban or industrial targets		
1. Baseline exchange	5,000	57	20	0.1 to 10	10,400
2. Low-yield airbursts	5,000	10	33	0.1 to 1	22,500†
9. 10,000-MT‡ maximum	10,000	63	15	0.1 to 10	16,160
10. 3,000-MT exchange	3,000	50	25	0.3 to 5	5,433
11. 3,000-MT counterforce	3,000	70	0	1 to 10	2,150
12. 1,000-MT exchange§	1,000	50	25	0.2 to 1	2,250
13. 300-MT Southern Hemisphere‖	300	0	50	1.	300
14. 100-MT city attack¶	100	0	100	0.1	1,000
16. Silos, "severe" case#	5,000	100	0	5 to 10	700
18. 25,000-MT‡ "future war"	25,000	72	10	0.1 to 10	28,300†

*Case numbers correspond to a complete list given in (*15*). Detailed detonation inventories are not reproduced here. Except as noted, attacks are concentrated in the NH. Baseline dust and smoke parameters are described in Tables 2 and 3. †Assumes more extensive MIRVing of existing missiles and some possible new deployment of medium- and long-range missiles (*20–23*). ‡Although these larger total yields might imply involvement of the entire globe in the war, for ease of comparison hemispherically averaged results are still considered. §Nominal area of wildfires is reduced from 5×10^5 to 5×10^4 km^2. ‖Nominal area of wildfires is reduced from 5×10^5 to 5×10^3 km^2. ¶The central city burden of combustibles is 20 g/cm^2 (twice that in the baseline case) and the net fire smoke emission is 0.026 g per gram of material burned. There is a negligible contribution to the opacity from wildfires and dust. #Includes a sixfold increase in the fine dust mass lofted per megaton of yield.

The properties of nuclear dust and smoke are critical to the present analysis. The basic parameterizations are described in Tables 2 and 3, respectively; details may be found in (*15*). For each explosion scenario, the fundamental quantities that must be known to make optical and climate predictions are the total atmospheric injections of fine dust (≤ 10 μm in radius) and soot.

Nuclear explosions at or near the ground can generate fine particles by several mechanisms (*27*): (i) ejection and disaggregation of soil particles (*29*), (ii) vaporization and renucleation of earth and rock (*30*), and (iii) blowoff and sweepup of surface dust and smoke (*31*). Analyses of nuclear test data indicate that roughly 1×10^5 to 6×10^5 tons of dust per megaton of explosive yield are held in the stabilized clouds of land surface detonations (*32*). Moreover, size analysis of dust samples collected in nuclear clouds indicates a substantial submicrometer fraction (*33*). Nuclear surface detonations may be much more efficient in generating fine dust than volcanic eruptions (*15, 34*), which have been used inappropriately in the past to estimate the impacts of nuclear war (*2*).

The intense light emitted by a nuclear fireball is sufficient to ignite flammable materials over a wide area (*27*). The explosions over Hiroshima and Nagasaki both initiated massive conflagrations (*35*). In each city, the region heavily damaged by blast was also consumed by fire (*36*). Assessments over the past two decades strongly suggest that widespread fires would occur after most nuclear bursts over forests and cities (*37–44*). The Northern Hemisphere has $\approx 4 \times 10^7$ km^2 of forest land, which holds combustible material averaging ~ 2.2 g/cm^2 (*7*). The world's urban and suburban zones cover an area of $\approx 1.5 \times 10^6$ km^2 (*15*). Central cities, which occupy 5 to 10 percent of the total urban area, hold ≈ 10 to 40 g/cm^2 of combustible material, while residential areas hold ≈ 1 to 5 g/cm^2 (*41, 42, 44, 45*). Smoke emissions from wildfires and large-scale urban fires probably lie in the range of 2 to 8 percent by mass of the fuel burned (*46*). The highly absorbing sooty fraction (principally graphitic carbon) could comprise up to 50 percent of the emission by weight (*47, 48*). In wildfires, and probably urban fires, ≥ 90 percent of the smoke mass consists of particles < 1 μm in radius (*49*). For calculations at visible wavelengths, smoke particles are assigned an imaginary part of the refractive index of 0.3 (*50*).

Simulations

The model predictions discussed here generally represent effects averaged over the Northern Hemisphere (NH). The initial nuclear explosions and fires would be largely confined (*51*) to northern mid-latitudes (30° to 60°N). Accordingly, the predicted mean dust and smoke opacity could be larger by a factor of 2 to 3 at mid-latitudes, but smaller elsewhere. Hemispherically averaged optical depths at visible wavelengths (*52*) for the mixed nuclear dust and smoke clouds corresponding to the scenarios in Table 1 are shown in Fig. 1. The vertical optical depth is a convenient diagnostic of nuclear cloud properties and may be used roughly to scale atmospheric light levels and temperatures for the various scenarios.

In the baseline scenario (case 1, 5000 MT), the initial NH optical depth is ≃ 4, of which ≃ 1 is due to stratospheric dust and ≃ 3 to tropospheric smoke. After 1 month the optical depth is still ≃ 2. Beyond 2 to 3 months, dust dominates the optical effects, as the soot is largely depleted by rainout and washout (*54*). In the baseline case, about 240,000 km² of urban area is partially (50 percent) burned by ≃ 1000 MT of explosions (only 20 percent of the total exchange yield). This roughly corresponds to one sixth of the world's urbanized land area, one fourth of the developed area of the NH, and one half of the area of urban centers with populations > 100,000 in the NATO and Warsaw Pact countries. The mean quantity of combustible material consumed over the burned area is ≃ 1.9 g/cm². Wildfires ignited by the remaining 4000 MT of yield burn another 500,000 km² of forest, brush, and grasslands (*7*, *39*, *55*), consuming ≃ 0.5 g/cm² of fuel in the process (*7*).

Total smoke emission in the baseline case is ≃ 225 million tons (released over several days). By comparison, the current annual global smoke emission is estimated as ≃ 200 million tons (*15*), but is probably < 1 percent as effective as nuclear smoke would be in perturbing the atmosphere (*56*).

The optical depth simulations for cases 1, 2, 9, and 10 in Fig. 1 show that a range of exchanges between 3000 and 10,000 MT might create similar effects. Even cases 11, 12, and 13, while less severe in their absolute impact, produce optical depths comparable to or exceeding those of a major volcanic eruption. It is noteworthy that eruptions such as Tambora in 1815 may have produced significant climate perturbations, even with an average surface temperature decrease of ≤ 1 K (*57–60*).

Case 14 represents a 100-MT attack on cities with 1000 100-KT warheads. In the attack, 25,000 km² of built-up urban area is burned (such an area could be accounted for by ≃ 100 major cities). The smoke emission is computed with fire parameters that differ from the baseline case. The average burden of combustible material in city centers is 20 g/cm² (versus 10 g/cm² in case 1) and the average smoke emission factor is 0.026 gram of smoke per gram of material burned (versus the conservative figure of 0.011 g/g adopted for central city fires in the baseline case). About 130 million tons of urban smoke is injected into the troposphere in each case (none reaches the stratosphere in case 14). In the baseline case, only about 10 percent of the urban smoke originates from fires in city centers (Table 3).

The smoke injection threshold for ma-

Table 2. Dust parameterization for the baseline case.

*Materials in stabilized nuclear explosion clouds**

Type of burst	Dust mass (ton/MT):	Dust size distribution† [r_m(μm)/σ/α]:	H_2O (ton/MT):
Land surface	3.3×10^5	0.25/2.0/4.0	1.0×10^5
Land near-surface	1.0×10^5	0.25/2.0/4.0	1.0×10^5

Dust composition: siliceous minerals and glasses

Index of refraction at visible wavelengths‡: $n = 1.50 - 0.001\,i$

Stabilized nuclear cloud top and bottom heights, z_t and z_b, for surface and low-air bursts§: $z_t = 21\,Y^{0.2}$; $z_b = 13\,Y^{0.2}$; where Y = yield in megatons

Multiburst interactions are ignored

Baseline dust injections

Total dust ≃ 9.6×10^8 tons; 80 percent in the stratosphere; 8.4 percent < 1 μm in radius

Submicrometer dust injection is ~ 25 ton/KT for surface bursts, which represents ~ 0.5 percent of the total ejecta mass

Total initial area of stabilized fireballs ≃ 2.0×10^6 km²

*Materials are assumed to be uniformly distributed in the clouds. †Particle size distributions (number/cm³ – μm radius) are log-normal with a power-law tail at large sizes. The parameters r_m and σ are the log-normal number mode radius and size variance, respectively, and α is the exponent of the $r^{-\alpha}$ dependence at large sizes. The log-normal and power-law distributions are connected at a radius of ≃ 1 μm (*15*). ‡The refractive indices of dust at infrared wavelengths are discussed in (*10*). §The model of Foley and Ruderman (*87*) is adopted, but with the cloud heights lowered by about 0.5 km. The original cloud heights are based on U.S. Pacific test data, and may overestimate the heights at mid-latitudes by several kilometers.

Table 3. Fire and smoke parameterization for the baseline case.

Fire area and emissions

Area of urban fire ignition defined by the 20 cal/cm² thermal irradiance contour (≃ 5 psi peak overpressure contour) with an average atmospheric transmittance of 50 percent: A (km²) = 250 Y, where Y = yield in megatons detonated over cities; overlap of fire zones is ignored

Urban flammable material burdens average 3 g/cm² in suburban areas and 10 g/cm² in city centers (5 percent of the total urban area)

Average consumption of flammables in urban fires is 1.9 g/cm²

Average net smoke emission factor is 0.027 g per gram of material burned (for urban centers it is only 0.011 g/g)

Area of wildfires is 5×10^5 km² with 0.5 g/cm² of fuel burned, and a smoke emission factor of 0.032 g/g

Long-term fires burn 3×10^{14} g of fuel with an emission factor of 0.05 g/g

Fire plume heights (top and bottom altitudes)

Urban fires: 1 to 7 km

Fire storms (5 percent of urban fires): $z_b \leq 5$ km; $z_t \leq 19$ km

Wildfires: 1 to 5 km

Long-term fires: 0 to 2 km

Fire duration

Urban fires, 1 day; wildfires, 10 days; long-term fires, 30 days

Smoke properties

Density, 1.0 g/cm³; complex index of refraction, $1.75 - 0.30\,i$; size distribution, log-normal with r_m(μm)/σ = 0.1/2.0 for urban fires and 0.05/2.0 for wildfires and long-term fires

Baseline smoke injections

Total smoke emission ≃ 2.25×10^8 tons, 5 percent in the stratosphere

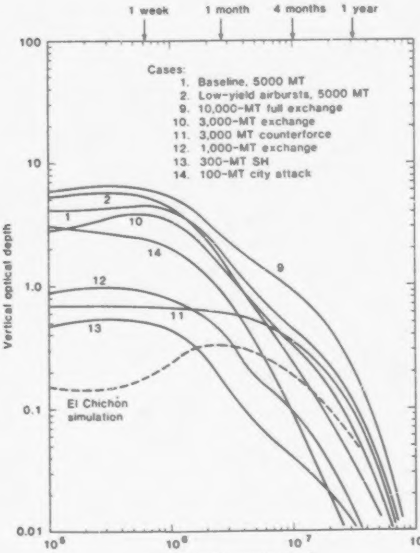
Urban-suburban fires account for 52 percent of emissions, fire storms for 7 percent, wildfires for 34 percent, and long-term fires for 7 percent

Total area burned by urban-suburban fires is 2.3×10^5 km²; fire storms, 1.2×10^4 km²; and wildfires, 5.0×10^5 km² jor optical perturbations on a hemispheric scale appears to lie at $\approx 1 \times 10^8$ tons. From case 14, one can envision the release of $\approx 1 \times 10^6$ tons of smoke from each of 100 major city fires consuming $\approx 4 \times 10^7$ tons of combustible material per city. Such fires could be ignited by 100 MT of nuclear explosions. Unexpectedly, less than 1 percent of the existing strategic arsenals, if targeted on cities, could produce optical (and climatic) disturbances much larger than those previously associated with a massive nuclear exchange of $\approx$ 10,000 MT (*2*).

Figure 2 shows the surface temperature perturbation over continental land areas in the NH calculated from the dust and smoke optical depths for several scenarios. Most striking are the extremely low temperatures occurring within 3 to 4 weeks after a major exchange. In the baseline 5000-MT case, a minimum land temperature of $\approx$ 250 K (−23°C) is predicted after 3 weeks. Subfreezing temperatures persist for several months. Among the cases shown, even the smallest temperature decreases on land are $\approx$ 5° to 10°C (cases 4, 11, and 12), enough to turn summer into winter. Thus, severe climatological consequences might be expected in each of these cases. The 100-MT city airburst scenario (case 14) produces a 2-month interval of subfreezing land temperatures, with a minimum again near 250 K. The temperature recovery in this instance is hastened by the absorption of sunlight in optically thin remnant soot clouds (see below). Comparable exchanges with and without smoke emission (for instance, cases 10 and 11) show that the tropospheric soot layers cause a sudden surface cooling of short duration, while fine stratospheric dust is responsible for prolonged cooling lasting a year or more. [Climatologically, a long-term surface cooling of only 1°C is significant (*60*).] In all instances, nuclear dust acts to cool the earth's surface; soot also tends to cool the surface except when the soot cloud is both optically thin and located near the surface [an unimportant case because only relatively small transient warmings $\leq$ 2 K can thereby be achieved (*61*)].

Predicted air temperature variations over the world's oceans associated with changes in atmospheric radiative transport are always small (cooling of $\leq$ 3 K) because of the great heat content and rapid mixing of surface waters. However, variations in atmospheric zonal circulation patterns (see below) might significantly alter ocean currents and upwelling, as occurred on a smaller scale recently in the Eastern Pacific (El Niño) (*62*). The oceanic heat reservoir would also moderate the predicted continental land temperature decreases, particularly in coastal regions (*10*). The effect is difficult to assess because disturbances in atmospheric circulation patterns are likely. Actual temperature decreases in continental interiors might be roughly 30 percent smaller than predicted here, and along coastlines 70 percent smaller (*10*). In the baseline case, therefore, continental temperatures may fall to $\approx$ 260 K before returning to ambient.

Predicted changes in the vertical temperature profile for the baseline nuclear exchange are illustrated as a function of time in Fig. 3. The dominant features of the temperature perturbation are a large warming (up to 80 K) of the lower stratosphere and upper troposphere, and a large cooling (up to 40 K) of the surface and lower troposphere. The warming is caused by absorption of solar radiation in the upper-level dust and smoke clouds; it persists for an extended period because of the long residence time of the particles at high altitudes. The size of the warming is due to the low heat capacity of the upper atmosphere, its small infrared emissivity, and the initially low temperatures at high altitudes. The surface cooling is the result of attenuation of the incident solar flux by the aerosol clouds (see Fig. 4) during the first month of the simulation. The greenhouse effect no longer occurs in our calculations because



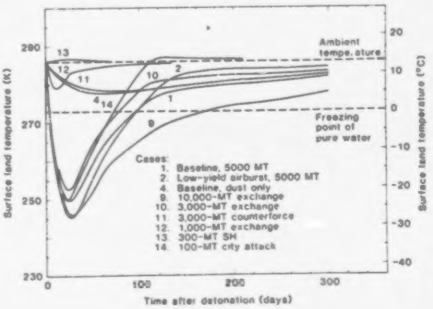


Fig. 1 (left). Time-dependent hemispherically averaged vertical optical depths (scattering plus absorption) of nuclear dust and smoke clouds at a wavelength of 550 nm. Optical depths $\leq$ 0.1 are negligible, ~ 1 are significant, and > 2 imply possible major consequences. Transmission of sunlight becomes highly nonlinear at optical depths $\geq$ 1. Results are given for several of the cases in Table 1. Calculated optical depths for the expanding El Chichón eruption cloud are shown for comparison (*53*). Fig. 2 (right). Hemispherically averaged surface temperature variations after a nuclear exchange. Results are shown for several of the cases in Table 1. (Note the linear time scale, unlike that in Fig. 1). Temperatures generally apply to the interior of continental land masses. Only in cases 4 and 11 are the effects of fires neglected.

solar energy is deposited above the height at which infrared energy is radiated to space.

Decreases in insolation for several nuclear war scenarios are shown in Fig. 4. The baseline case implies average hemispheric solar fluxes at the ground ≤ 10 percent of normal values for several weeks (apart from any patchiness in the dust and smoke clouds). In addition to causing the temperature declines mentioned above, the attenuated insolation could affect plant growth rates, and vigor in the marine (*63*), littoral, and terrestrial food chains. In the 10,000-MT "severe" case, average light levels are below the minimum required for photosynthesis for about 40 days over much of the Northern Hemisphere. In a number of other cases, insolation may, for more than 2 months, fall below the compensation point at which photosynthesis is just sufficient to maintain plant metabolism. Because nuclear clouds are likely to remain patchy the first week or two after an exchange, leakage of sunlight through holes in the clouds could enhance plant growth activity above that predicted for average cloud conditions; however, soon thereafter the holes are likely to be sealed.

Sensitivity Tests

A large number of sensitivity calculations were carried out as part of this study (*15*). The results are summarized here. Reasonable variations in the nuclear dust parameters in the baseline scenario produce initial hemispherically averaged dust optical depths varying from about 0.2 to 3.0. Accordingly, nuclear dust alone could have a major climatic impact. In the baseline case, the dust opacity is much greater than the total aerosol opacity associated with the El Chichón and Agung eruptions (*59*, *64*); even when the dust parameters are assigned their least adverse values within the plausible range, the effects are comparable to those of a major volcanic explosion.

Figure 5 compares nuclear cloud optical depths for several variations of the baseline model smoke parameters (with dust included). In the baseline case, it is assumed that fire storms inject only a small fraction (≈ 5 percent) of the total smoke emission into the stratosphere (*65*). Thus, case 1 and case 3 (no firestorms) are very similar. As an extreme excursion, all the nuclear smoke is injected into the stratosphere and rapidly dispersed around the globe (case 26); large optical depths can then persist for a year (Fig. 5). Prolongation of optical effects is also obtained in case 22, where the tropospheric washout lifetime of smoke particles is increased from 10 to 30 days near the ground. By contrast, when the nuclear smoke is initially contained near the ground and dynamical and hydrological removal processes are assumed to be unperturbed, smoke depletion occurs much faster (case 25). But even in this case, some of the smoke still diffuses to the upper troposphere and remains there for several months (*66*).

In a set of optical calculations, the imaginary refractive index of the smoke was varied between 0.3 and 0.01. The optical depths calculated for indices between 0.1 and 0.3 show virtually no differences (cases 1 and 27 in Fig. 5). At an index of 0.05, the absorption optical depth (*52*) is reduced by only ≈ 50 percent, and at 0.01, by ≈ 85 percent. The overall opacity (absorption plus scattering), moreover, increases by ≈ 5 percent. These results show that light absorption and heating in nuclear smoke clouds remain high until the graphitic carbon fraction of the smoke falls below a few percent.

One sensitivity test (case 29, not illustrated) considers the optical effects in the Southern Hemisphere (SH) of dust and soot transported from the NH stratosphere. In this calculation, the smoke in the 300-MT SH case 13 is combined with half the baseline stratospheric dust and smoke (to approximate rapid global dispersion in the stratosphere). The initial optical depth is ≈ 1 over the SH, dropping to about 0.3 in 3 months. Predicted average SH continental surface temperatures fall by 8 K within several weeks and remain at least 4 K below normal for nearly 8 months. The seasonal influence should be taken into account, however. For example, the worst consequences for the NH might result from a spring or

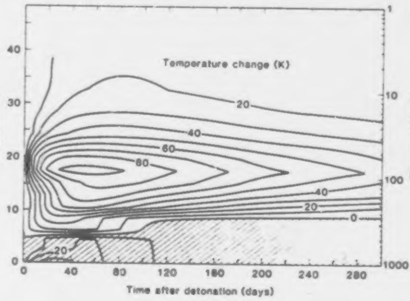


Fig. 3. Northern Hemisphere troposphere and stratosphere temperature perturbations (in Kelvins; 1 K = 1°C) after the baseline nuclear exchange (case 1). The hatched area indicates cooling. Ambient pressure levels in millibars are also given.

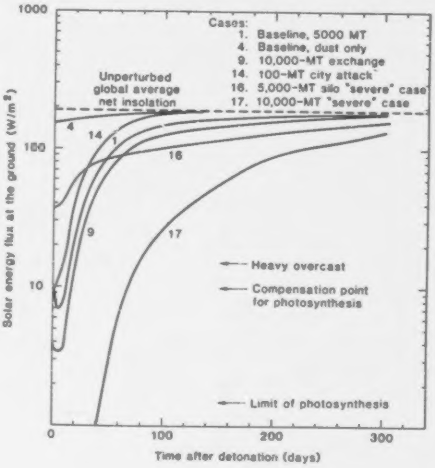


Fig. 4. Solar energy fluxes at the ground over the Northern Hemisphere in the aftermath of a nuclear exchange. Results are given for several of the cases in Table 1. (Note the linear time scale.) Solar fluxes are averaged over the diurnal cycle and over the hemisphere. In cases 4 and 16 fires are neglected. Also indicated are the approximate flux levels at which photosynthesis cannot keep pace with plant respiration (compensation point) and at which photosynthesis ceases. These limits vary for different species.

summer exchange, when crops are vulnerable and fire hazards are greatest. The SH, in its fall or winter, might then be least sensitive to cooling and darkening. Nevertheless, the implications of this scenario for the tropical regions in both hemispheres appear to be serious and worthy of further analysis. Seasonal factors can also modulate the atmospheric response to perturbations by smoke and dust, and should be considered.

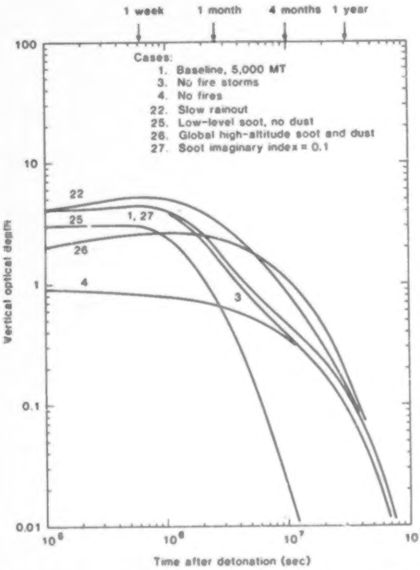
A number of sensitivity tests for more severe cases were run with exchange yields ranging from 1000 to 10,000 MT and smoke and dust parameters assigned more adverse, but not implausible, values. The predicted effects are substantially worse (see below). The lower probabilities of these severe cases must be weighed against the catastrophic outcomes which they imply. It would be prudent policy to assess the importance of these scenarios in terms of the product of their probabilities and the costs of their corresponding effects. Unfortunately, we are unable to give an accurate quantitative estimate of the relevant probabilities. By their very nature, however, the severe cases may be the most important to consider in the deployment of nuclear weapons.

With these reservations, we present the optical depths for some of the more severe cases in Fig. 6. Large opacities can persist for a year, and land surface temperatures can fall to 230 to 240 K, about 50 K below normal. Combined with low light levels (Fig. 4), these severe scenarios raise the possibility of widespread and catastrophic ecological consequences.

Two sensitivity tests were run to determine roughly the implications for optical properties of aerosol agglomeration in the early expanding clouds. (The simulations already take into account continuous coagulation of the particles in the dispersed clouds.) Very slow dispersion of the initial stabilized dust and smoke clouds, taking nearly 8 months to cover the NH, was assumed. Coagulation of particles reduced the average opacity after 3 months by about 40 percent. When the adhesion efficiency of the colliding particles was also maximized, the average opacity after 3 months was reduced by ≈ 75 percent. In the most likely situation, however, prompt agglomeration and coagulation might reduce the average hemispheric cloud optical depths by 20 to 50 percent.

Other Effects

We also considered, in less detail, the long-term effects of radioactive fallout, fireball-generated NO_x, and pyrogenic toxic gases (*15*). The physics of radioactive fallout is well known (*2, 5, 12, 27, 67*). Our calculations bear primarily on the widespread intermediate time scale accumulation of fallout due to washout and dry deposition of dispersed nuclear dust (*68*). To estimate possible exposure



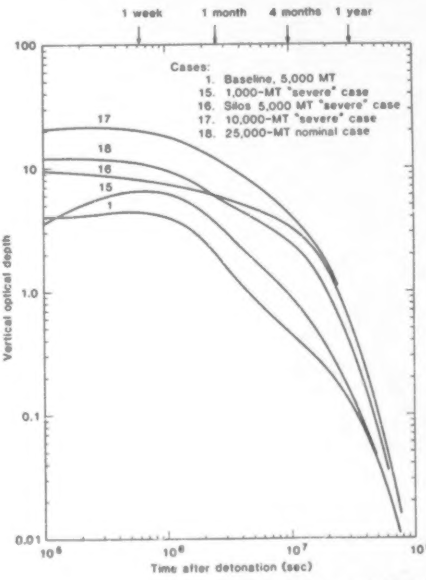


Fig. 5 (left). Time-dependent vertical optical depths (absorption plus scattering at 550 nm) of nuclear clouds, in a sensitivity analysis. Optical depths are average values for the Northern Hemisphere. All cases shown correspond to parameter variations of the baseline model (case 1) and include dust appropriate to it: case 3, no fire storms; case 4, no fires; case 22, smoke rainout rate decreased by a factor of 3; case 25, smoke initially confined to the lowest 3 km of the atmosphere; case 26, smoke initially distributed between 13 and 19 km over the entire globe; and case 27, smoke imaginary part of refractive index reduced from 0.3 to 0.1. For comparison, in case 4, only dust from the baseline model is considered (fires are ignored). Fig. 6 (right). Time-dependent vertical optical depths (absorption plus scattering at 550 nm) for enhanced cases of explosion yield or nuclear dust and smoke production. Conditions are detailed elsewhere (*15*). Weapon yield inventories are identical to the nominal cases of the same total yield described in Table 1 (cases 16 and 18 are also listed there). The "severe" cases generally include a sixfold increase in fine dust injection and a doubling of smoke emission. In cases 15, 17, and 18, smoke causes most of the opacity during the first 1 to 2 months. In cases 17 and 18, dust makes a major contribution to the optical effects beyond 1 to 2 months. In case 16, fires are neglected and dust from surface bursts produces all of the opacity.

levels, we adopt a fission yield fraction of 0.5 for all weapons. For exposure to only the gamma emission of radioactive dust that begins to fall out after 2 days in the baseline scenario (5000 MT), the hemispherically averaged total dose accumulated by humans over several months could be ≈ 20 rads, assuming no shelter from or weathering of the dust. Fallout during this time would be confined largely to northern mid-latitudes; hence the dose there could be ≈ 2 to 3 times larger (*69*, *70*). Considering ingestion of biologically active radionuclides (*27*, *71*) and occasional exposure to localized fallout, the average total chronic mid-latitude dose of ionizing radiation for the baseline case could be ≥ 50 rads of whole-body external gamma radiation, plus ≥ 50 rads to specific body organs from internal beta and gamma emitters (*71*, *72*). In a 10,000-MT exchange, under the same assumptions, these mean doses would be doubled. Such doses are roughly an order of magnitude larger than previous estimates, which neglected intermediate time scale washout and fallout of tropospheric nuclear debris from low-yield (< 1-MT) detonations.

The problem of NO_x produced in the fireballs of high-yield explosions, and the resulting depletion of stratospheric ozone, has been treated in a number of studies (*2–4*, *7*, *73*). In our baseline case a maximum hemispherically averaged ozone reduction of ≈ 30 percent is found. This would be substantially smaller if individual warhead yields were all reduced below 1 MT. Considering the relation between solar UV-B radiation increases and ozone decreases (*74*), UV-B doses roughly twice normal are expected in the first year after a baseline exchange (when the dust and soot had dissipated). Large UV-B effects could accompany exchanges involving warheads of greater yield (or large multiburst laydowns).

A variety of toxic gases (pyrotoxins) would be generated in large quantities by nuclear fires, including CO and HCN. According to Crutzen and Birks (*7*), heavy air pollution, including elevated ozone concentrations, could blanket the NH for several months. We are also concerned about dioxins and furans, extremely persistent and toxic compounds which are released during the combustion of widely used synthetic organic chemicals (*75*). Hundreds of tons of dioxins and furans could be generated during a nuclear exchange (*76*). The long-term ecological consequences of such nuclear pyrotoxins seem worthy of further consideration.

Meteorological Perturbations

Horizontal variations in sunlight absorption in the atmosphere, and at the surface, are the fundamental drivers of atmospheric circulation. For many of the cases considered in this study, sizable changes in the driving forces are implied. For example, temperature contrasts greater than 10 K between NH continental areas and adjacent oceans may induce a strong monsoonal circulation, in some ways analogous to the wintertime pattern near the Indian subcontinent. Similarly, the temperature contrast between debris-laden atmospheric regions and adjacent regions not yet filled by smoke and dust will cause new circulation patterns.

Thick clouds of nuclear dust and smoke can thus cause significant climatic perturbations, and related effects, through a variety of mechanisms: reflection of solar radiation to space and absorption of sunlight in the upper atmosphere, leading to overall surface cooling; modification of solar absorption and heating patterns that drive the atmospheric circulation on small scales (*77*) and large scales (*78*); introduction of excess water vapor and cloud condensation nuclei, which affect the formation of clouds and precipitation (*79*); and alteration of the surface albedo by fires and soot (*80*). These effects are closely coupled in determining the overall response of the atmosphere to a nuclear war (*81*). It is not yet possible to forecast in detail the changes in coupled atmospheric circulation and radiation fields, and in weather and microclimates, which would accompany the massive dust and smoke injections treated here. Hence speculation must be limited to the most general considerations.

Water evaporation from the oceans is a continuing source of moisture for the marine boundary layer. A heavy semipermanent fog or haze layer might blanket large bodies of water. The consequences for marine precipitation are not clear, particularly if normal prevailing winds are greatly modified by the perturbed solar driving force. Some continental zones might be subject to continuous snowfall for several months (*10*). Precipitation can lead to soot removal, although this process may not be very efficient for nuclear clouds (*77*, *79*). It is likely that, on average, precipitation rates would be generally smaller than in the ambient atmosphere; the major remaining energy source available for storm genesis is the latent heat from ocean evaporation, and the upper atmosphere is warmer than the lower atmosphere which suppresses convection and rainfall.

Despite possible heavy snowfalls, it is unlikely that an ice age would be triggered by a nuclear war. The period of cooling (≤ 1 year) is probably too short to overcome the considerable inertia in the earth's climate system. The oceanic heat reservoir would probably force the climate toward contemporary norms in the years after a war. The CO_2 input from nuclear fires is not significant climatologically (*7*).

Interhemispheric Transport

In earlier studies it was assumed that significant interhemispheric transport of nuclear debris and radioactivity requires a year or more (*2*). This was based on observations of transport under ambient conditions, including dispersion of debris clouds from individual atmospheric nuclear weapons tests. However, with dense clouds of dust and smoke produced by thousands of nearly simultaneous explosions, large dynamical disturbances would be expected in the aftermath of a nuclear war. A rough analogy can be drawn with the evolution of global-scale dust storms on Mars. The lower martian atmosphere is similar in density to the earth's stratosphere, and the period of rotation is almost identical to the earth's (although the solar insolation is only half the terrestrial value). Dust storms that develop in one hemisphere on Mars often rapidly intensify and spread over the entire planet, crossing the equator in a mean time of ≈ 10 days (*15*, *82*, *83*). The explanation apparently lies in the heating of the dust aloft, which then dominates other heat sources and drives the circulation. Haberle *et al.* (*82*) used a two-dimensional model to simulate the evolution of martian dust storms and found that dust at low latitudes, in the core of the Hadley circulation, is the most important in modifying the winds. In a nuclear exchange, most of the dust and smoke would be injected at middle latitudes. However, Haberle *et al.* (*82*) could not treat planetary-scale waves in their calculations. Perturbations of planetary wave amplitudes may be critical in the transport of nuclear war debris between middle and low latitudes.

Significant atmospheric effects in the SH could be produced (i) through dust and smoke injection resulting from explosions on SH targets, (ii) through transport of NH debris across the meteorological equator by monsoon-like winds (*84*), and (iii) through interhemispheric transport in the upper troposphere and stratosphere, driven by solar heating of nuclear dust and smoke clouds. Photometric observations of the El Chichón volcanic eruption cloud (origin, 14°N) by the Solar Mesosphere Explorer satellite show that 10 to 20 percent of the stratospheric aerosol had been transported to the SH after ≈ 7 weeks (*85*).

Discussion and Conclusions

The studies outlined here suggest severe long-term climatic effects from a 5000-MT nuclear exchange. Despite uncertainties in the amounts and properties of the dust and smoke produced by nuclear detonations, and the limitations of models available for analysis, the following tentative conclusions may be drawn.

1) Unlike most earlier studies [for instance, (*2*)], we find that a global nuclear war could have a major impact on climate—manifested by significant surface darkening over many weeks, subfreezing land temperatures persisting for up to several months, large perturbations in global circulation patterns, and dramatic changes in local weather and precipitation rates—a harsh "nuclear winter" in any season. Greatly accelerated interhemispheric transport of nuclear debris in the stratosphere might also occur, although modeling studies are needed to quantify this effect. With rapid interhemispheric mixing, the SH could be subjected to large injections of nuclear debris soon after an exchange in the Northern Hemisphere. In the past, SH effects have been assumed to be minor. Although the climate disturbances are expected to last more than a year, it seems unlikely that a major long-term climatic change, such as an ice age, would be triggered.

2) Relatively large climatic effects could result even from relatively small nuclear exchanges (100 to 1000 MT) if urban areas were heavily targeted, because as little as 100 MT is sufficient to devastate and burn several hundred of the world's major urban centers. Such a low threshold yield for massive smoke emissions, although scenario-dependent, implies that even limited nuclear exchanges could trigger severe aftereffects. It is much less likely that a 5000- to 10,000-MT exchange would have only minor effects.

3) The climatic impact of sooty smoke from nuclear fires ignited by airbursts is expected to be more important than that of dust raised by surface bursts (when both effects occur). Smoke absorbs sunlight efficiently, whereas soil dust is generally nonabsorbing. Smoke particles are extremely small (typically < 1 μm in radius), which lengthens their atmospheric residence time. There is also a high probability that nuclear explosions over cities, forests, and grasslands will ignite widespread fires, even in attacks limited to missile silos and other strategic military targets.

4) Smoke from urban fires may be more important than smoke from collateral forest fires for at least two reasons: (i) in a full-scale exchange, cities holding large stores of combustible materials are likely to be attacked directly; and (ii) intense fire storms could pump smoke into the stratosphere, where the residence time is a year or more.

5) Nuclear dust can also contribute to the climatic impact of a nuclear exchange. The dust-climate effect is very sensitive to the conduct of the war; a smaller effect is expected when lower yield weapons are deployed and airbursts dominate surface land bursts. Multiburst phenomena might enhance the climatic effects of nuclear dust, but not enough data are available to assess this issue.

6) Exposure to radioactive fallout may be more intense and widespread than predicted by empirical exposure models, which neglect intermediate fallout extending over many days and weeks, particularly when unprecedented quantities of fission debris are released abruptly into the troposphere by explosions with submegaton yields. Average NH mid-latitude whole-body gamma-ray doses of up to 50 rads are possible in a 5000-MT exchange; larger doses would accrue within the fallout plumes of radioactive debris extending hundreds of kilometers downwind of targets. These estimates neglect a probably significant internal radiation dose due to biologically active radionuclides.

7) Synergisms between long-term nuclear war stresses—such as low light levels, subfreezing temperatures, exposure to intermediate time scale radioactive fallout, heavy pyrogenic air pollution, and UV-B flux enhancements—aggravated by the destruction of medical facilities, food stores, and civil services, could lead to many additional fatalities, and could place severe stresses on the global ecosystem. An assessment of the possible long-term biological consequences of the nuclear war effects quantified in this study is made by Ehrlich *et al.* (*86*).

Our estimates of the physical and chemical impacts of nuclear war are necessarily uncertain because we have used one-dimensional models, because the data base is incomplete, and because the problem is not amenable to experimental investigation. We are also unable to forecast the detailed nature of the changes in atmospheric dynamics and meteorology implied by our nuclear war scenarios, or the effect of such changes on the maintenance or dispersal of the initiating dust and smoke clouds. Nevertheless, the magnitudes of the first-order effects are so large, and the implications so serious, that we hope the scientific issues raised here will be vigorously and critically examined.

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19. Prediction of circulation anomalies and attendant changes in regional weather patterns requires an appropriately designed three-dimensional general circulation model with at least the following features: horizontal resolution of 10° or better, high vertical resolution through the troposphere and stratosphere, cloud and precipitation parameterizations that allow for excursions well outside present-day experience, ability to transport dust and smoke particles, an interactive radiative transport scheme to calculate dust and smoke effects on light fluxes and heating rates, allowance for changes in particle sizes with time and for wet and dry deposition, and possibly a treatment of the coupling between surface winds and ocean currents and temperatures. Even if such a model were available today, it would not be able to resolve questions of patchiness on horizontal scales of less than several hundred kilometers, of local-

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28. The areas cited are subject to peak overpressures ≥ 10 to 20 cal/cm^2.
29. A 1-MT surface explosion ejects ~ 5×10^6 tons of debris, forming a large crater (*27*). Typical soils consist of ≈ 5 to 25 percent by weight of grains ≤ 1 μm in radius [G. A. D'Almeida and L. Schutz, *J. Climate Appl. Meteorol.* 22, 233 (1983); G. Rawson, private communication]. However, the extent of disaggregation of the soil into parent grain sizes is probably ≤ 10 percent [R. G. Pinnick, G. Fernandez, B. D. Hinds, *Appl. Opt.* 22, 95 (1983)] and would depend in part on soil moisture and compaction.
30. A 1-MT surface explosion vaporizes ≈ 2×10^4 to 4×10^4 tons of soil (*27*), which is ingested by the fireball. Some silicates and other refractory materials later renucleate into fine glassy spheres [M. W. Nathans, R. Thews, I. J. Russell, *Adv. Chem. Ser.* 93, 360 (1970)].
31. A 1-MT surface explosion raises significant quantities of dust over an area of ≥ 100 km^2 by "popcorning," due to thermal radiation, and by saltation, due to pressure winds and turbulence (*27*). Much of the dust is sucked up by the afterwinds behind the rising fireball. Size sorting should favor greatest lifting for the finest particles. The quantity of dust lofted would be sensitive to soil type, moisture, compaction, vegetation cover, and terrain. Probably > 1×10^5 tons of dust per megaton can be incorporated into the stabilized clouds in this manner.
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34. Atmospheric dust from volcanic explosions differs in several important respects from that produced by nuclear explosions. A volcanic eruption represents a localized dust source, while a nuclear war would involve thousands of widely distributed sources. The dust mass concentration in stabilized nuclear explosion clouds is low (≤ 1 g/m^3), while volcanic eruption columns are so dense they generally collapse under their own weight [G. P. L. Walker, *J. Volcanol. Geotherm. Res.* 11, 81 (1981)]. In the dense volcanic clouds particle agglomeration, particularly under the influence of electrical charge, can lead to accelerated removal by sedimentation [S. N. Carey and H. Sigurdsson, *J. Geophys. Res.* 87, 7061 (1982); S. Brazier *et al.*, *Nature (London)* 301 115 (1983)]. The size distribution of volcanic ash is also fundamentally different from that of nuclear dust [W. I. Rose *et al.*, *Am. J. Sci.* 280, 671 (1980)], because the origins of the particles are so different. The injection efficiency of nuclear dust into the stratosphere by megaton-yield explosions is close to unity, while the injection efficiency of fine volcanic dust appears to be very low (*15*). For these reasons and others, the observed climatic effects of major historical volcanic eruptions cannot be used, as in (*2*), to calibrate the potential climatic effect of nuclear dust merely by scaling energy or soil volume. However, in cases where the total amount of submicrometer volcanic material that remained in the stratosphere could be determined, climate models have been applied and tested [J. B. Pollack *et al.*, *J. Geophys. Res.* 81, 1071 (1976)]. We used such a model in this study to predict the effects of specific nuclear dust injections.
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45. Urban and suburban areas of cities with populations exceeding 100,000 (about 2300 worldwide) are surveyed in (*15*). Also discussed are global reserves of flammable substances, which are shown to be roughly consistent with known rates of production and accumulation of combustible materials. P. J. Crutzen and I. E. Galbally (in preparation) reach similar conclusions about global stockpiles of combustibles.
46. Smoke emission data for forest fires are reviewed by D. V. Sandberg, J. M. Pierovich, D. G. Fox, and E. W. Ross ["Effects of fire on air," *U.S. Forest Serv. Tech. Rep. WO-9* (1979)]. Largest emission factors occur in intense large-scale fires where smoldering and flaming exist simultaneously, and the oxygen supply may be limited over part of the burning zone. Smoke emissions from synthetic organic compounds would generally be larger than those from forest fuels [C. P. Bankston, B. T. Zinn, R. F. Browner, E. A. Powell, *Combust. Flame* 41, 273 (1981)].
47. Sooty smoke is a complex mixture of oils, tars, and graphitic (or elemental) carbon. Measured benzene-soluble mass fractions of wildfire smokes fall in the range ≈ 40 to 75 percent [D. V. Sandberg *et al.* in (*46*)]. Most of the residue is likely to be brown to black (the color of smoke ranges from white, when large amounts of water vapor are present, to yellow or brown, when oils predominate, to gray or black, when elemental carbon is a major component).
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49. In wildfires, the particle number mode radius is typically about 0.05 μm [D. V. Sandberg *et al.*, in (*46*)]. For burning synthetics the number mode radius can be substantially greater, but a reasonable average value is 0.1 μm [C. P. Bankston *et al.*, in (*46*)]. Often, larger debris particles and firebrands are swept up by powerful fire winds, but they have short atmospheric residence times and are not included in the present estimates (C. K. McMahon and P. W. Ryan, paper presented at the 69th Annual Meeting, Air Pollution Control Association, Portland, Ore., 27 June to 1 July 1976). Nevertheless, because winds exceeding 100 km/hour may be generated in large-scale fires, significant quantities of fine noncombustible surface dust and explosion debris (such as pulverized plaster) might be lifted in addition to the smoke particles.
50. This assumes an average graphitic carbon mass fraction of about 30 to 50 percent, for a pure carbon imaginary refractive index of 0.6 to 1.0 [J. T. Twitty and J. A. Weinman, *J. Appl. Meteorol.* 10, 725 (1971); S. Chippett and W. A. Gray, *Combust. Flame* 31, 149 (1978)]. The real part of the refractive index of pure carbon is 1.75, and for many oils is 1.5 to 1.6. Smoke particles were assigned an average density of 1 g/cm^3 (C. K. McMahon, paper presented at the 76th Annual Meeting, Air Pollution Control Association, Atlanta, Ga., 19 to 24 June 1983). Solid graphite has a density ≈ 2.5 g/cm^3, and most oils, ≤ 1 g/cm^3.
51. A number of targets with military, economic, or political significance can also be identified in tropical northern latitudes and in the SH (*20*).
52. Attenuation of direct sunlight by dust and smoke particles obeys the law $I/I_0 = \exp(-\tau/\mu_0)$, where τ is the total extinction optical depth due to photon scattering and absorption by the particles and μ_0 is the cosine of the solar zenith angle. The optical depth depends on the wavelength of the light and the size distribution and composition of the particles, and is generally calculated from Mie theory (assuming equivalent spherical particles). The total light intensity at the ground consists of a direct component and a diffuse, or scattered, component, the latter usually calculated with a radiative transfer model. The extinction optical depth can be written as $\tau = XML$, where X is the specific cross section (m^2/g particulate), M the suspended particle mass concentration (g/m^3), and L the path length (m). It is the sum of a scattering and an absorption optical depth ($\tau = \tau_s + \tau_a$). Fine dust and smoke particles have scattering coefficients $X_s \approx 3$ to 5 m^2/g at visible wavelengths. However, the absorption coefficients X_a are very sensitive to the imaginary part of the index of refraction. For typical soil particles, $X_a \leq 0.1$ m^2/g. For smokes, X_a can vary from ~ 0.1 to 10 m^2/g, roughly in proportion to the volume fraction of graphite in the particles. Occasionally, specific extinction coefficients for smoke are given relative to the mass of fuel burned; then X implicitly includes a multiplicative emission factor (grams of smoke generated per gram of fuel burned).
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55. To estimate the wildfire area, we assume that 25 percent of the total nonurban yield, or 1000 MT, ignites fires over an area of 500 km^2/MT—approximately the zone irradiated by 10 cal/cm^2—and that the fires do not spread outside this zone (*39*). R. E. Huschke [*Rand Corp. Rep. RM-5073-TAB* (1966)] analyzed the simultaneous flammability of wildland fuels in the United States, and determined that about 50 percent of all fuels are at least moderately flammable throughout the summer months. Because ≈ 50 percent of the land areas of the countries likely to be involved in a nuclear exchange are covered by forest and brush, which are flammable about 50 percent of the time, the 1000-MT ignition yield follows statistically.
56. Most of the background smoke is injected into the lowest 1 to 2 km of the atmosphere, where it has a short lifetime, and consists on the average of ≤ 10 percent graphitic carbon [R. P. Turco, O. B. Toon, R. C. Whitten, J. B. Pollack, P. Hamill, in *Precipitation Scavenging, Dry Deposition and Resuspension*, H. R. Pruppacher, R. G. Semonin, W. G. N. Slinn, Eds. (Elsevier, New York, 1983), p. 1337]. Thus, the average optical depth of ambient atmospheric soot is only ≤ 1 percent of the initial optical depth of the baseline nuclear war smoke pall.
57. H. E. Landsberg and J. M. Albert, *Weatherwise* 27, 63 (1974).
58. H. Stommel and E. Stommel, *Sci. Am.* 240, 176 (June 1979).
59. O. B. Toon and J. B. Pollack, *Nat. Hist.* 86, 8 (January 1977).
60. H. H. Lamb, *Climate Present, Past and Future* (Methuen, London, 1977), vols. 1 and 2.
61. Notwithstanding possible alterations in the surface albedo due to the fires and deposition of soot (*15*, *80*).
62. S. G. H. Philander, *Nature (London)* 302, 295 (1983); B. C. Weare, *Science* 221, 947 (1983).
63. D. H. Milne and C. P. McKay, *Geol. Soc. Am. Spec. Pap. 190* (1982), p. 297.
64. O. B. Toon, *Eos* 63, 901 (1982).
65. The stratosphere is normally defined as the region of constant or increasing temperature with increasing height lying just above the tropo-

sphere. The residence time of fine particles in the stratosphere is considerably longer than in the upper troposphere because of the greater stability of the stratospheric air layers and the absence of precipitation in the stratosphere. With large smoke injections, however, the ambient temperature profile would be substantially distorted (for instance, see Fig. 3) and a "stratosphere" might form in the vicinity of the smoke cloud, increasing its residence time at all altitudes (*15*). Thus the duration of sunlight attenuation and temperature perturbations in Figs. 1 to 6 may be considerably underestimated.

66. Transport of soot from the boundary layer into the overlying free troposphere can occur by diurnal expansion and contraction of the boundary layer, by large-scale advection, and by strong localized convection.
67. F. Barnaby and J. Rotblat, *Ambio* **11**, 84 (1982).
68. The term "intermediate" fallout distinguishes the radioactivity deposited between several days and ~ 1 month after an exchange from "prompt" fallout (≲ 1 day) and "late" fallout (months to years). Intermediate fallout is expected to be at least hemispheric in scale and can still deliver a significant chronic whole-body gamma-ray dose. It may also contribute a substantial internal dose, for example, from ^{131}I. The intermediate time scale gamma-ray dose represents, in one sense, the minimum average exposure far from targets and plumes of prompt fallout. However, the geographic distribution of intermediate fallout would still be highly variable, and estimates of the average dose made with a one-dimensional model are greatly idealized. The present calculations were calibrated against the observed prompt fallout of nuclear test explosions (*15*).
69. There is also reason to believe that the fission yield fraction of nuclear devices may be increasing as warhead yields decrease and uranium processing technology improves. If the fission fraction were unity, our dose estimates would have to be doubled. We also neglect additional potential sources of radioactive fallout from salted "dirty" weapons and explosions over nuclear reactors and fuel reprocessing plants.
70. J. Knox (*Lawrence Livermore Lab. Rep. UCRL-89907*, in press) reports fallout calculations which explicitly account for horizontal spreading and transport of nuclear debris clouds. For a 5300-MT strategic exchange, Knox computes average whole-body gamma-ray doses of 20 rads from 40° to 60°N, with smaller average doses elsewhere. Hot spots of up to 200 rads over areas of ~ 10^6 km^2 are also predicted for intermediate time scale fallout. These calculations are consistent with our estimates.
71. H. Lee and W. E. Strope [*Stanford Res. Inst. Rep. EGU 2981* (1974)] studied U.S. exposure to transoceanic fallout generated by several assumed Sino-Soviet nuclear exchanges. Taking into account weathering of fallout debris, protection by shelters, and a 5-day delay before initial exposure, potential whole-body gamma-ray doses ≲ 10 rads and internal doses ≳ 10 to 100 rads, mainly to the thyroid and intestines, were estimated.
72. These estimates assume normal rates and patterns of precipitation, which control the intermediate time scale radioactive fallout. In severely perturbed cases, however, it may happen that the initial dispersal of the airborne radioactivity is accelerated by heating, but that intermediate time scale deposition is suppressed by lack of precipitation over land.
73. H. Johnston, G. Whitten, J. Birks, *J. Geophys. Res.* **78**, 6107 (1973); H. S. Johnston, *ibid.* **82**, 3119 (1977).
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75. M. P. Esposito, T. O. Tiernan, F. E. Dryden, *U.S. EPA Rep. EPA-600/280-197* (1980).
76. J. Josephson, *Environ. Sci. Technol.* **17**, 124A (1983). In burning of PCB's, for example, release of toxic polycyclic chlorinated organic compounds can amount to 0.1 percent by weight. In the United States more than 300,000 tons of PCB's are currently in use in electrical systems [S. Miller, *Environ. Sci. Technol.* **17**, 11A (1983)].
77. C.-S. Chen and H. D. Orville [*J. Appl. Meteorol.* **16**, 401 (1977)] model the effects of fine graphitic dust on cumulus-scale convection. They show that strong convective motions can be established in still air within 10 minutes after the injection of a kilometer-sized cloud of submicrometer particles of carbon black, at mixing ratios ≲ 50 ppb by mass. Addition of excess humidity in their model to induce rainfall results in still stronger convection; the carbon dust is raised higher and spread farther horizontally, while ≲ 20 percent is scavenged by the precipitation. W. M. Gray, W. M. Frank, M. L. Corrin, and C. A. Stokes [*J. Appl. Meteorol.* **15**, 355 (1976)] discuss possible mesoscale (≳ 100 km) weather modifications due to large carbon dust injections.
78. C. Covey, S. Schneider, and S. Thompson (in preparation) report GCM simulations which include soot burdens similar to those in our baseline case. They find major perturbations in the global circulation within a week of injection, with strong indications that some of the nuclear debris at northern mid-latitudes would be transported upward and toward the equator.
79. R. C. Eagan, P. V. Hobbs, L. F. Radke, *J. Appl. Meteorol.* **13**, 553 (1974).
80. C. Sagan, O. B. Toon, and J. B. Pollack [*Science* **206**, 1363 (1979)] discuss the impact of anthropogenic albedo changes on global climate. Nuclear war may cause albedo changes by burning large areas of forest and grassland; by generating massive quantities of soot which can settle out on plants, snowfields, and ocean surface waters; and by altering the pattern and extent of ambient water clouds. The nuclear fires in the baseline case consume an area ≈ 7.5×10^5 km^2, or only ≈ 0.5 percent of the global landmass; it is doubtful that an albedo variation over such a limited area is significant. All the soot in the baseline nuclear war case, if spread uniformly over the earth, would amount to a layer ~0.5 μm thick. Even if the soot settled out uniformly on all surfaces, the first rainfall would wash it into soils and watersheds. The question of the effect of soot on snow and ice fields is under debate (J. Birks, private communication). In general, soot or sand accelerates the melting of snow and ice. Soot that settles in the oceans would be rapidly removed by nonselective filter-feeding plankton, if these survived the initial darkness and ionizing radiation.
81. In the present calculations, chemical changes in stratospheric O_3 and NO_2 concentrations cause a small average temperature perturbation compared to that caused by nuclear dust and smoke; it seems unlikely that chemically induced climatic disturbances would be a major factor in a nuclear war. Tropospheric ozone concentrations, if tripled (*7*), would lead to a small greenhouse warming of the surface [W. C. Wang, Y. L. Yung, A. A. Lacis, T. Mo, J. E. Hansen, *Science* **194**, 685 (1976)]. This might result in more rapid surface temperature recovery. However, the tropospheric O_3 increase is transient (~ 3 months in duration) and probably secondary in importance to the contemporaneous smoke and dust perturbations.
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83. During the martian dust storm of 1971–1972, the IRIS experiment on Mariner 9 observed that suspended particles heated the atmosphere and produced a vertical temperature gradient that was substantially subadiabatic [R. B. Hanel *et al.*, *Icarus* **17**, 423 (1972); J. B. Pollack *et al.*, *J. Geophys. Res.* **84**, 2929 (1979)].
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88. We gratefully acknowledge helpful discussions with J. Berry, H. A. Bethe, C. Billings, J. Birks, H. Brode, R. Cicerone, L. Colin, P. Crutzen, R. Decker, P. J. Dolan, P. Dyal, F. J. Dyson, P. Ehrlich, B. T. Feld, R. L. Garwin, F. Gilmore, L. Grinspoon, M. Grover, J. Knox, A. Kuhl, C. Leovy, M. MacCracken, J. Mahlman, J. Marcum, P. Morrison, E. Patterson, R. Perret, G. Rawson, J. Rotblat, E. E. Salpeter, S. Soter, P. Speed, E. Teller, and R. Whitten on a variety of subjects related to this work. S. H. Schneider, C. Covey, and S. Thompson of the National Center for Atmospheric Research generously shared with us preliminary GCM calculations of the global weather effects implied by our smoke emissions. We also thank the almost 100 participants of a 5-day symposium held in Cambridge, Mass., 22 to 26 April, for reviewing our results; that symposium was organized by the Conference on the Longterm Worldwide Biological Consequences of Nuclear War under a grant from the W. Alton Jones Foundation. Special thanks go to Janet M. Tollas for compiling information on world urbanization, to May Liu for assistance with computer programming, and to Mary Maki for diligence in preparing the manuscript.

Long-Term Biological Consequences of Nuclear War

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Summary. Subfreezing temperatures, low light levels, and high doses of ionizing and ultraviolet radiation extending for many months after a large-scale nuclear war could destroy the biological support systems of civilization, at least in the Northern Hemisphere. Productivity in natural and agricultural ecosystems could be severely restricted for a year or more. Postwar survivors would face starvation as well as freezing conditions in the dark and be exposed to near-lethal doses of radiation. If, as now seems possible, the Southern Hemisphere were affected also, global disruption of the biosphere could ensue. In any event, there would be severe consequences, even in the areas not affected directly, because of the interdependence of the world economy. In either case the extinction of a large fraction of the Earth's animals, plants, and microorganisms seems possible. The population size of *Homo sapiens* conceivably could be reduced to prehistoric levels or below, and extinction of the human species itself cannot be excluded.

Recent studies of large-scale nuclear war (5000- to 10,000-MT yields) have estimated that there would be 750 million immediate deaths from blast alone (*1*); a total of about 1.1 billion deaths from the combined effects of blast, fire, and radiation (*2*); and approximately an additional 1.1 billion injuries requiring medical attention (*1, 2*). Thus, 30 to 50 percent of the total human population could be immediate casualties of a nuclear war. The vast majority of the casualties would be in the Northern Hemisphere, especially in the United States, the U.S.S.R., Europe, and Japan. These enormous numbers have typically been taken to define the full potential catastrophe of such a war. New evidence presented here, however, suggests that the longer term biological effects resulting from climatic changes may be at least as serious as the immediate ones. Our concern in this article is with the 2 billion to 3 billion people not killed immediately, including those in nations far removed from the nuclear conflict.

We consider primarily the results of a nuclear war in which sufficient dust and soot are injected into the atmosphere to attenuate most incident solar radiation, a possibility first suggested by Ehrlich *et al.* (*3*), and first shown quantitatively and brought to wide attention by Crutzen and Birks (*1*). In a wide range of nuclear exchange scenarios, with yields from 100 MT up to 10,000 MT, we now know that enough sunlight could be absorbed and scattered to cause widespread cold and darkness [(*4, 5*); these papers are also collectively referred to as TTAPS]. In each of these cases the computations indicate very serious biological consequences. This is so even though all the scenarios are well within current capabilities and do not seem to be strategically implausible (*1, 2, 4–6*). Furthermore, the probability of nuclear wars of very high yield may have been generally underestimated (*7*). We also examine the consequences of the spread of atmospheric effects from the Northern to the Southern Hemisphere (*4, 5*).

As a reference case, we consider case 17 of the nuclear war scenarios discussed in TTAPS. This is a 10,000-MT exchange in which parameters describing the properties of dust and soot aerosols are assigned adverse but not implausible values and in which 30 percent of the soot is carried by fire storms to stratospheric altitudes. The resulting environmental perturbations, with their ranges of uncertainty, are listed for the Northern Hemisphere and the Southern Hemisphere in Table 1, A and B.

As an average over the Northern Hemisphere, independent of the season of the year, calculated fluxes of visible light would be reduced to approximately 1 percent of ambient, and surface temperatures in continental interiors could fall to approximately −40°C. At least a year would be required for light and temperature values to recover to their normal conditions. In target zones, it might initially be too dark to see, even at midday. An estimated 30 percent of Northern Hemisphere mid-latitude land areas would receive a dose ≥ 500 R immediately after the explosions. This dose, from external gamma-emitters in radioactive fallout, would be comparable to or more than the acute mean lethal dose (LD$_{50}$) for healthy adults (*8*). Over the next few days and weeks, fallout would contribute an additional external dose of ≥ 100 R over 50 percent of northern mid-latitudes. Internal doses would contribute another ≥ 100 R concentrated in specific body systems, such as thyroid, bones, the gastrointestinal

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This article was prepared following a meeting of biologists on the Long-Term Worldwide Biological Consequences of Nuclear War (Cambridge, Massachusetts, 25 and 26 April 1983). The consensus of the 40 scientists at the meeting is presented here, assembled by a committee consisting of: Paul R. Ehrlich, Stanford University; John Harte, University of California, Berkeley; Mark A. Harwell, Cornell University; Peter H. Raven, Missouri Botanical Garden; Carl Sagan, Cornell University; George M. Woodwell, Marine Biological Laboratory, Woods Hole; Joseph Berry, Carnegie Institute of Washington; Edward S. Ayensu, Smithsonian Institution; Anne H. Ehrlich, Stanford University; Thomas Eisner, Cornell University; Stephen J. Gould, Harvard University; Herbert D. Grover, University of New Mexico; Rafael Herrera, IVIC, Venezuela; Robert M. May, Princeton University; Ernst Mayr, Harvard University; Christopher P. McKay, National Research Council Associate; Harold A. Mooney, Stanford University; Norman Myers, Oxford, England; David Pimentel, Cornell University; and John M. Teal, Woods Hole Oceanographic Institution. The findings in this article were presented at the Conference on the World after Nuclear War, Washington, D.C., 31 October and 1 November 1983. Reprint requests should be sent to the Conference on the Long-Term Worldwide Biological Consequences of Nuclear War, 1735 New York Avenue, NW, Washington, D.C. 20006.

tract, and the milk of lactating mothers (*9*). After settling of the dust and smoke, the surface flux of near-ultraviolet solar radiation (UV-B, 320 to 290 nm) would be increased severalfold for some years, because of the depletion of the ozonosphere by fireball-generated NO_x. Southern Hemisphere effects would involve minimum light levels < 10 percent of ambient, minimum land surface temperatures < −18°C, and UV-B increments of tens of percent for years. The potential impacts from the climatic changes that would be induced by nuclear war are outlined in Table 2.

Thermonuclear wars that would be less adverse to the environment are clearly possible, but climatic effects similar to those just outlined could well result from much more limited exchanges, down to several hundred megatons, if cities were targeted (*4, 5*). Even if there were no global climatic effects, the regional consequences of nuclear war might be serious (Table 3). We believe, however, that decision-makers should be fully apprised of the potential consequences of the scenarios most likely to trigger long-term effects. For this reason we have concentrated in this article on the 10,000-MT severe case rather than the 5000-MT nominal baseline case of TTAPS. Because of synergisms, however, the consequences of any particular nuclear war scenario are likely to be still more severe than discussed below. We still have too incomplete an understanding of the detailed workings of global ecosystems to evaluate all the interactions, and thus the cumulative effects, of the many stresses to which people and ecosystems would be subjected. Every unassessed synergism is likely to have an incremental negative effect.

Temperature

The impact of dramatically reduced temperatures on plants would depend on the time of year at which they occurred, their duration, and the tolerance limits of the plants. The abrupt onset of cold is of particular importance. Winter wheat, for

Table 1. Long-term stresses on the biosphere in (A) the Northern Hemisphere and (B) the Southern Hemisphere following a 10,000-MT severe Northern Hemisphere exchange (*4, 5*). Stresses occur simultaneously. Their geographic extent and severity would depend on many factors, including the number, distribution, and yield of the weapons detonated; height above the surface of the explosions and scale of the subsequent fires; degree of atmospheric transport of soot and dust (especially from the Northern to the Southern Hemisphere); and rate of washout of soot and dust, which determines their atmospheric residence times. Stresses in (B) are estimated effects which arise from 100-MT total detonations in the Southern Hemisphere plus particulates transported from the Northern Hemisphere primarily in the stratosphere. Data are from the "baseline 5000 MT" and "100-MT city attack" cases (*4, 5*). The Southern Hemisphere effects could be more severe if a heavy stratospheric soot burden resulted.

Physical parameter	Perturbed value*	Duration	Area affected†	Possible range
		A. Northern Hemisphere		
Sunlight intensity	× 0.01	1.5 months	NML	× 0.003 to 0.03
	× 0.05	3 months	NML	× 0.01 to 0.15
	× 0.25	5 months	NH	× 0.1 to 0.7
	× 0.50	8 months	NH	× 0.3 to 1.0
Land surface temperature‡	−43°C	4 months	NML land	−53° to −23°C
	−23°C	9 months	NH land	−33° to −3°C
	−3°C	1 year	NH land	−13° to +7°C
UV-B radiation§	× 4	1 year	NH	× 2 to 8
	× 3	3 years	NH	× 1 to 5
Radioactive fallout exposure‖	≥ 500 R	1 hour to 1 day	30 percent NML land	
	≥ 100 R	1 day to 1 month	50 percent NML	Factor of 3
	≥ 10 R	≥ 1 month	50 percent NH	
Fallout burdens§,¶	^{131}I, 4 × 10^5 MCi	8 days#	NML	
	^{106}Ru, 1 × 10^4 MCi	1 year	NH	
	^{90}Sr, 400 MCi	30 years	NH	
	^{137}Cs, 650 MCi	30 years	NH	
		B. Southern Hemisphere		
Sunlight intensity	× 0.1	1 month	SH tropics	0.03 to 0.3
	× 0.5	2 months	SH tropics and SML	0.1 to 0.9
	× 0.8	4 months	SH	0.3 to 1.0
Land surface temperature‡	−18°C	1 month	SML land	−33° to −3°C
	−3°C	2 months	SML land	−23° to +7°C
	+7°C	10 months	SML land	−13° to +13°C
UV-B radiation§	× 1.5	1 year	SH	× 1.2 to 2.0
	× 1.2	3 years	SH	× 1.0 to 1.5
Radioactive fallout exposure‖	≥ 500 R	1 hour to 1 day	Near detonation sites	
	10 to 100 R	1 day to 1 month	SH land	Factor of 3
Fallout burdens§,¶	^{90}Sr, 300 MCi	30 years	SH	
	^{137}Cs, 330 MCi	30 years	SH	

*The following definitions apply: ×, multiplicative factor; R, rad = rem; MCi, megacurie. †Abbreviations: NH, Northern Hemisphere; NML, northern mid-latitudes; SH, Southern Hemisphere; SML, southern mid-latitudes. ‡Average surface temperatures should be compared to the normal ambient value of 13°C. §From (*4, 5, 22*). ‖These figures are rough estimates of whole-body gamma-ray doses and apply only to exposed organisms, particularly near or downwind of the 10^4 explosion sites. Exposures are due to fallout on "prompt" and "intermediate" time scale; ingestion of biologically active radionuclides is not taken into account, but could double the dose in body organs (for instance, the thyroid for ^{131}I), where these radionuclides tend to accumulate. Doses are larger than in some conventional models which scale from high-yield atmospheric tests; such models assume much more radioactivity carried into the stratosphere and decaying before falling out than is appropriate for a war with a wide mix of yields (*4, 5, 40*). ¶The principal modes of deposition are fallout and washout. In airbursts, the radionuclides settle out slowly over several years. In surface bursts, ≈ 60 percent falls out promptly, ≈ 40 percent over 1 to 2 years. In subsurface water bursts, ~ 100 percent is deposited in the water. During the atmospheric nuclear tests of the 1950's and 1960's, ~ 200 MT of fission yield produced an average ^{90}Sr deposition ~ 50 millicuries per square kilometer. #These are essentially the radionuclide lifetimes. Other radionuclides contribute mainly to the prompt fallout exposure.

example, can tolerate temperatures as low as −15° to −20°C when preconditioned to cold temperatures (as occurs naturally in fall and winter months), but the same plants may be killed by −5°C if exposed during active summer growth (*10*). Even plants from alpine regions, *Pinus cembra* for example, may tolerate temperatures as low as −50°C in midwinter but may be killed by temperatures of −5° to −10°C occurring in summer (*11*). In the TTAPS calculations, temperatures are expected to fall rapidly to their lowest levels (Table 1); it is unlikely under these circumstances that normally cold-

Table 2. Potential impacts on humans and ecosystems from climatic changes induced by a major nuclear war at various time periods after the war.

First few months	End of first year	Next decade
	Natural ecosystems: Terrestrial	
Extreme cold, independent of season and widespread over the Earth, would severely damage plants, particularly in mid-latitudes in the Northern Hemisphere and in the tropics. Particulates obscuring sunlight would severely curtail photosynthesis, essentially eliminating plant productivity. Extreme cold, unavailability of fresh water, and near darkness would severely stress most animals, with widespread mortality. Storm events of unprecedented intensity would devastate ecosystems, especially at margins of continents.	Many hardy perennial plants and most seeds of temperate plants would survive, but plant productivity would continue to be depressed significantly. As the atmosphere clears, increased UV-B would damage plants and impair vision systems of many animal species. Limited primary productivity would cause intense competition for resources among animals. Many tropical species would continue to suffer fatalities or reduced productivity from temperature stress. Widespread extinction of vertebrates.	Basic potential for primary and secondary productivity would gradually recover; however, extensive irreversible damage to ecosystems would have occurred. Ecosystem structure and processes would continue to respond unstably to perturbations and a long period of time might follow before functional redundancies would reestablish ecosystem homeostasis. Massive loss of species, especially in tropical areas, would lead to reduced genetic and species diversity.
	Natural ecosystems: Aquatic	
Temperature extremes would result in widespread ice formation on most freshwater bodies, particularly in the Northern Hemisphere and in mid-latitude continental areas. Marine ecosystems would be largely buffered from extreme temperatures, with effects limited to coastal and shallow tropical areas. Light reductions would essentially terminate phytoplankton productivity, eliminating the support base for many marine and freshwater animal species. Storms at continental margins would stress shallow-water ecosystems and add to sediment loadings. Potential food sources would not be accessible to humans or would be contaminated by radionuclides and toxic substances.	Early loss of phytoplankton would continue to be felt in population collapses in many herbivore and carnivore species in marine ecosystems; benthic communities would not be as disrupted. Freshwater ecosystems would begin to thaw, but many species would have been lost. Organisms in temperate marine and freshwater systems adapted to seasonal temperature fluctuations would recover more quickly and extensively than in tropical regions.	Recovery would proceed more rapidly than for terrestrial ecosystems. Species extinctions would be more likely in tropical areas. Coastal marine ecosystems would begin to contain harvestable food sources, although contamination could continue.
	Agroecosystems	
Extreme temperatures and low light levels could preclude virtually any net productivity in crops anywhere on Earth. Supplies of food in targeted areas would be destroyed, contaminated, remote, or quickly depleted. Nontargeted importing countries would lose subsidies from North America and other food exporters.	Potential crop productivity would remain low because of continued, though much less extreme, temperature depressions. Sunlight would not be limiting but would be enriched with UV-B. Reduced precipitation and loss of soil from storm events would reduce potential productivity. Organized agriculture would be unlikely, and modern subsidies of energy, fertilizers, pesticides, and so on, would not be available. Stored food would be essentially depleted, and potential draught animals would have suffered extensive fatalities and consumption by humans	Biotic potential for crop production would largely be restored. Limiting factors for reestablishment of agriculture would be related to human support for water, energy, fertilizers pest and disease protection, and so on.
	Human-societal systems	
Survivors of immediate effects (from blast, fire, and initial ionizing radiation) would include perhaps 50 to 75 percent of the Earth's population. Extreme temperatures, near darkness, violent storms, and loss of shelter and fuel supplies would result in widespread fatalities from exposure, starvation, lack of drinking water, and synergisms with other impacts such as radiation exposure, malnutrition, lack of medical systems, and psychological stress. Societal support systems for food, energy, transportation, medical care, communications, and so on, would cease to function.	Climatic impacts would be considerably reduced, but exposure would remain a stress on humans. Loss of agricultural support would dominate adverse human health impacts. Societal systems could not be expected to function and support humans. With the return of sunlight and UV-B, widespread eye damage could occur. Psychological stresses, radiation exposures, and many synergistic stresses would continue to affect humans adversely. Epidemics and pandemics would be likely.	Climatic stresses would not be the primary limiting factors for human recovery. Rates of reestablishment of societal order and human support systems would limit rates of human population growth. Human carrying capacities could remain severely depressed from prewar conditions for a very long period of time, at best.

tolerant plants could "harden" (develop freezing tolerance) before lethal temperatures were reached. Other stresses to plants from radiation, air pollutants, and low light levels immediately after the war would compound the damage caused by freezing. In addition, diseased or damaged plants have a reduced capacity to harden to freezing conditions (*11*).

Even temperatures considerably above freezing can be damaging to some plants. For example, exposure of rice or sorghum to a temperature of only 13°C at the critical time can inhibit grain formation because the pollen produced is sterile (*11*). Corn (*Zea mays*) and soybeans (*Glycine max*), two important crops in North America, are quite sensitive to temperatures below about 10°C.

While a nuclear war in the fall or winter would probably have a lesser effect on plants in temperate regions than one in the spring or summer, tropical vegetation is vulnerable to low temperatures throughout the year. The only areas in which terrestrial plants might not be devastated by severe cold would be immediately along the coasts and on islands, where the temperatures would be moderated by the thermal inertia of the oceans. These areas, however, would experience particularly violent weather because of the large lateral temperature gradient between oceans and continental interiors.

Visible Light

The disruption of photosynthesis by the attenuation of incident sunlight would have consequences that cascade through food chains, many of which include people as consumers. Primary productivity would be reduced roughly in proportion to the degree of light attenuation, even making the unrealistic assumption that the vegetation would remain otherwise undamaged.

Many studies have examined the effects of shading on the rate of photosynthesis, plant growth, and crop yield (*12*). Although individual leaves may be saturated by light levels below one-half of unattenuated sunlight, entire plants that have several layers of leaves oriented at different angles to the sun and partially shading each other are usually not light-saturated. Thus, while only a 10 percent reduction in light might not reduce photosynthesis in a fully exposed leaf, it might well reduce it in the entire plant because of the presence of unsaturated leaves within the canopy. Because plants also respire, most would, in fact, be unlikely to maintain any net growth if the light level fell below about 5 percent of the normal ambient levels in their habitats (the compensation point) (*12, 13*). At the levels expected in the early months following a substantial nuclear exchange, plants would be severely affected and many would die because of the substantial reductions in their net productivity caused by reduced light alone.

Ionizing Radiation

Exposures to ionizing radiation in a nuclear exchange would result directly from the gamma and neutron flux of the fireball, from the radioactive debris deposited downwind of the burst, and from the component of the debris that becomes airborne and circulates globally.

The degree of injury to organisms would depend on the rate and magnitude of the exposure, with higher rates and larger total exposures producing more severe effects. The mean lethal exposure for human beings is commonly thought to be 350 to 500 R received in the whole body in less than 48 hours. Most other mammals and some plants have mean lethal exposures of less than 1000 R. If the rate of exposure is lower, the mean lethal dose rises.

The area subject to intense radiation from the fireball would also be affected directly by blast and heat (*9, 14*). The radius within which the pressure from the blast exceeds 5 pounds per square inch has been defined as the lethal zone (*9*) for blast, and the area within which the thermal flux exceeds 10 cal/cm^2 as the lethal zone for heat. The radius within which ionizing radiation from the fireball would be expected to be lethal for human beings is less than the radii for mortality defined by pressure or heat (*1, 9*). No special further consideration has been given here to the effects of ionizing radiation from the fireballs.

One estimate, based on the *Ambio* scenario (*1*) and similar to the TTAPS baseline case, involves an exchange of 5742 MT and about 11,600 detonations without overlapping fallout fields; it suggests that about 5×10^6 km^2 would be exposed to 1000 R or more in downwind areas. About 85 percent of this total exposure would be received within 48 hours. Such an exposure is lethal to all exposed people and cause the death of sensitive plant species such as most conifers—trees that form extensive forests over most of the cooler parts of the Northern Hemisphere. If nuclear reactors, radioactive waste storage facilities, and fuel reprocessing plants are damaged during an exchange, the area affected and the levels of ionizing radiation could be even greater.

If we assume that approximately half of this area affected by fallout radiation in the range 1000 to 10,000 R is forested, there would be about 2.5×10^6 km^2 within which extensive mortality of trees and many other plants would occur (*15*). This would create the potential for extensive fires. Most conifers would die over an area amounting to about 2.5 percent of the entire land surface of the Northern Hemisphere.

The possibility that as much as 30 percent of the mid-latitude land area would be exposed to 500 R or more from gamma radiation emphasizes the scale and severity of the hazard (Table 1A). While 500 R of total exposure would have minor effects on most plant populations, it would cause widespread mortality among all mammals, including human beings. The unprotected survivors would be ill for weeks and more prone to cancer for the remainder of their lives. The total number of people afflicted would exceed 1 billion.

UV-B Radiation

In the weeks following the exchange, tropospheric and stratospheric dust and soot would absorb the UV-B flux that would otherwise be transmitted by the partially destroyed ozonosphere. But when the dust and soot cleared a few months later, the effects of O_3 depletion would be felt at the surface. In the Northern Hemisphere, the flux of UV-B would be enhanced for about a year by a factor of about 2 for the baseline TTAPS exchange and by a factor of 4 for the 10,000 MT war-treated in Table 1A. As is the case for an undepleted ozonosphere, the UV-B dose would be significantly greater at equatorial than at temperate latitudes.

Even much smaller O_3 depletions are considered dangerous to ecosystems and to people (*16*). If the entire UV-B band is enhanced by about 50 percent, the amount of UV-B at the higher energy end of the band, near 295 nm, would be increased by a factor of about 50. This region has particular biological significance because of the strong absorption of energy at these wavelengths by nucleic acids, aromatic amino acids, and the peptide bond. In large doses, UV-B is very destructive to plant leaves, weakening the plants and decreasing their productivity (*17*). Near-surface productivity of marine plankton is known to be depressed significantly by contemporary ambient UV-B levels; even small increases in UV-B could have "profound consequences" for the structure of marine food chains (*16*).

There are at least four additional ways in which increased levels of UV-B are known to be harmful to biological systems: (i) the immune systems of *Homo sapiens* and other mammals are known to be suppressed even by relatively low doses of UV-B (*18*). Especially under conditions of increased ionizing radiation and other physiological stress, such suppression of the immune systems leads to an increase in the incidence of disease. (ii) Plant leaves that reach maturity under low light intensities are two to three times more sensitive to UV-B than leaves that develop under high light intensities (*19*). (iii) Bacterial UV-B sensitivity is enhanced by low temperatures, which suppress the normal process of DNA repair, a process that is dependent on visible light (*16*). (iv) Protracted exposure to increased UV-B may induce corneal damage and cataracts, leading to blindness in human beings and terrestrial mammals (*20*). Thus the effects of increased UV-B may be among the most serious unanticipated consequences of nuclear war.

Atmospheric Effects

In a nuclear war, large quantities of air pollutants, including CO, O_3, NO_x, cyanides, vinyl chlorides, dioxins, and furans would be released near the surface (*4, 5, 21*). Smog and acid precipitation would be widespread in the aftermath of the nuclear exchange. These toxins might not have significant immediate effects on the vegetation that was already devastated, although, depending upon their persistence, they could certainly hinder its recovery. Their atmospheric transport by winds to more distant, initially unaffected ecosystems, on the other hand, might be an important additional effect. Large-scale fires coupled with an interruption of photosynthetic CO_2 uptake would produce a short-term increase in the atmospheric CO_2 concentration. The quantity of CO_2 now in the atmosphere is equivalent to that used by several years of photosynthesis and is further buffered by the inorganic carbon reserves of the ocean (*22*). Therefore, if the global climate and photosynthetic productivity of ecosystems recovered to near-normal levels within a few years, it is unlikely that any significant long-term change in the composition of the atmosphere would occur. It is not beyond the realm of possibility, however, that an event encompassing both hemispheres, with the ensuing damage to photosynthetic organisms, could cause a sudden increase in CO_2 concentration and thus long-term climatic changes. For comparison, the time scale for recycling of O_2 through the biosphere is about 2000 years (*23*).

Agricultural Systems

There is little storage of staple foods in human population centers, and most meat and fresh produce are supplied directly from farms. Only cereal grains are stored in significant quantities, but the sites at which they are stored often are located in areas remote from population centers. Following a spring or early summer war, the current year's crops would almost certainly be lost. Cereal crops would be harvested before a fall or winter war, but since the climate would remain unusually cold for many months, the following growing season would also be unfavorable for crop growth.

After a nuclear war, in short, the available potential supplies of food in the Northern Hemisphere would be destroyed or contaminated, located in inaccessible areas, or rapidly depleted. For nations experiencing the nuclear war di-

Table 3. Potential ecological consequences of the reference nuclear war, other than those induced by temperature and light reductions.

Stress	Intensity or extent	Mechanisms of effects	Ecosystem consequences
Local, global radioactive fallout from nuclear detonation*	≥ 100 rem average background; ≥ 200 rem over large area in Northern Hemisphere*	Direct health effects; immune system depression; differential radiosensitivities of species; genetic effects	Alteration in trophic structures; pest outbreaks; replacement by opportunistic species; genetic and ontogenetic anomalies
Enhanced UV-B	Fourfold increase over Northern Hemisphere*	Suppression of photosynthesis; direct health effects; differential sensitivities of species; damage to vision systems; immune system depression	Reduction in primary productivity; alterations in marine trophic structures; blindness in terrestrial animals; behavioral effects in insects including essential pollinators
Fire	Secondary fires widespread over Northern Hemisphere; ≥ 5 percent of terrestrial ecosystems affected	Direct loss of plants; damage to seed stores; changes in albedo; habitat destruction	Deforestation and desertification, which continues through positive feedback (*39*); local climatic changes; large-scale erosion and siltation; nutrient dumping; species extinction
Chemical pollution of surface waters	Pyrotoxins; release from chemical storage areas	Direct health effects; differential sensitivities of species; bioconcentration	Loss of organisms; continued contamination of surface and ground water systems; loss of water for human consumption
Chemical pollution of atmospheres	Major releases of NO, O_3 and pyrogenic pollutants from detonations; major releases of toxic organics from secondary fires in urban areas and chemical storage facilities	Direct health effects; differential sensitivities of species; acid precipitation	Widespread smog; freshwater acidification; nutrient dumping

*See Table 1A.

rectly, food resources would become scarce in a very short time. Further, nations that now require large imports of foods, including those untouched by nuclear detonations, would suffer an immediate interruption of the flow of food, forcing them to rely solely on their local agricultural and natural ecosystems. This would be very serious for many less-developed countries, especially those in the tropics.

Most major crops are annuals that are highly dependent on substantial energy and nutrient subsidies from human societies. Further, the fraction of their yields available for human consumption requires excess energy fixation beyond the respiratory needs of the plants, depending on full sunlight, on minimization of environmental stresses from pests, water insufficiency, particulates, and air pollution, and so on. Providing these conditions would be far more difficult, if not impossible, over much, if not all, of the Earth following a nuclear exchange. Agriculture as we know it would then, for all practical purposes, have come to an end.

Since the seeds for most North American, European, and Soviet crops are harvested and stored not on individual farms but predominantly in or near target areas, seed stocks for subsequent years would almost certainly be depleted severely, and the already limited genetic variability of those crops (*24*) would probably be reduced drastically. Furthermore, the potential crop-growing areas would experience local climatic changes, high levels of radioactive contamination, and impoverished or eroded soils. Recovery of agricultural production would have to occur in the absence of the massive energy subsidies (especially in the form of tractor fuel and fertilizers) to which agriculture in developed countries has become adapted (*25*).

Except along the coasts, continental precipitation would be reduced substantially for some time after a nuclear exchange (*4, 5*). Even now, rainfall is the major factor limiting crop growth in many areas, and irrigation, with requirements for energy and human support systems for pumping ground water, would not be available after a war. Moreover, in the months after the war, most of the available water would be frozen, and temperatures would recover slowly to normal values (*26*).

Temperate Terrestrial Ecosystems

The 2 billion to 3 billion survivors of the immediate effects of the war would be forced to turn to natural ecosystems as organized agriculture failed. Just at the time when these natural ecosystems would be asked to support a human population well beyond their carrying capacities, the normal functioning of the ecosystems themselves would be severely curtailed by the effects of nuclear war.

Subjecting these ecosystems to low temperature, fire, radiation, storm, and other physical stresses (many occurring simultaneously) would result in their increased vulnerability to disease and pest outbreaks, which might be prolonged. Primary productivity would be dramatically reduced at the prevailing low light levels; and, because of UV-B, smog, insects, radiation, and other damage to plants, it is unlikely that it would recover quickly to normal levels, even after light and temperature values had recovered. At the same time that their plant foods were being limited severely, most, if not all, of the vertebrates not killed outright by blast and ionizing radiation would either freeze or face a dark world where they would starve or die of thirst because surface waters would be frozen and thus unavailable. Many of the survivors would be widely scattered and often sick, leading to the slightly delayed extinction of many additional species.

Natural ecosystems provide civilization with a variety of crucial services in addition to food and shelter. These include regulation of atmospheric composition, moderation of climate and weather, regulation of the hydrologic cycle, generation and preservation of soils, degradation of wastes, and recycling of nutrients. From the human perspective, among the most important roles of ecosystems are their direct role in providing food and their maintenance of a vast library of species from which *Homo sapiens* has already drawn the basis of civilization (*27*). Accelerated loss of these genetic resources through extinction would be one of the most serious potential consequences of nuclear war.

Wildfires would be an important effect in north temperate ecosystems, their scale and distribution depending on such factors as the nuclear war scenario and the season. Another major uncertainty is the extent of fire storms, which might heat the lower levels of the soil enough to damage or destroy seed banks, especially in vegetation types not adapted to periodic fires. Multiple airbursts over seasonally dry areas such as California in the late summer or early fall could burn off much of the state's forest and brush areas, leading to catastrophic flooding and erosion during the next rainy season. Silting, toxic runoff, and rainout of radionuclides could kill much of the fauna of fresh and coastal waters, and concentrated radioactivity levels in surviving filter-feeding shellfish populations could make them dangerous to consume for long periods of time.

Other major consequences for terrestrial ecosystems resulting from nuclear war would include: (i) slower detoxification of air and water as a secondary result of damage to plants that now are important metabolic sinks for toxins; (ii) reduced evapotranspiration by plants contributing to a lower rate of entry of water into the atmosphere, especially over continental regions, and therefore a more sluggish hydrologic cycle; and (iii) great disturbance of the soil surface, leading to accelerated erosion and, probably, major dust storms (*28*).

Revegetation might superficially resemble that which follows local fires. Stresses from radiation, smog, erosion, fugitive dust, and toxic rains, however, would be superimposed on those of cold and darkness, thus delaying and modifying postwar succession in ways that would retard the restoration of ecosystem services (*29*). It is likely that most ecosystem changes would be short term. Some structural and functional changes, however, could be longer term, and perhaps irreversible, as ecosystems undergo qualitative changes to alternative stable states (*30*). Soil losses from erosion would be serious in areas experiencing widespread fires, plant death, and extremes of climate. Much would depend on the wind and precipitation patterns that would develop during the first postwar year (*4, 5*). The diversity of many natural communities would almost certainly be substantially reduced, and numerous species of plants, animals, and microorganisms would become extinct.

Tropical Terrestrial Ecosystems

The degree to which the tropics would be subjected to the sorts of conditions described above depends on factors such as the targeting pattern (*1, 6*), the prevalence of fire storms, the breakdown of the distinction between troposphere and stratosphere, and the rate of interhemispheric mixing as a function of altitude (*4, 5*). The spread of dense clouds of dust and soot and subfreezing temperatures to the northern tropics is highly likely, and to the Southern Hemisphere at least possible, so that it is appropriate to discuss the probable consequences of such a spread (*4, 5*) (Table 1B).

For example, the seeds of trees in tropical forests tend to be much more short-lived than those of temperate zones. If darkness or cold temperatures, or both, were to become widespread in the tropics, the tropical forests could largely disappear. This would lead to extinction of most of the species of plants, animals, and microorganisms on the Earth (*31, 32*), with long-term consequences of the greatest importance for the adaptability of human populations.

If darkness were widespread in the tropics, vast areas of tropical vegetation, which are considered very near the compensation point (*33*), would begin to respire away. In addition, many plants in tropical and subtropical regions do not have dormancy mechanisms that enable them to tolerate cold seasons, even at temperatures well above freezing. Even if the darkness and cold were confined mainly to temperate regions, pulses of cold air and soot could carry quick freezes well into the tropics. This would amount to an enhanced case of the phenomenon known as "friagem," which is used to describe the effects of cool temperatures spreading from temperate South America and entering the equatorial Amazon Basin, where they kill large numbers of birds and fish (*34*). One can predict from existing evidence on cooling effects during the Pleistocene and their consequences (*35*) that continental low-latitude areas would be severely affected by low air temperatures and decreased precipitation.

The dependence of tropical peoples on imported food and fertilizer would lead to severe effects, even if the tropics were not affected directly by the war. Large numbers of people would be forced to leave the cities and attempt to cultivate the remaining areas of forest, accelerating their destruction and the consequent rate of extinction. These activities would also greatly increase the amount of soot in the atmosphere, owing to improvised slash-and-burn agriculture on a vast scale. Regardless of the exact distribution of the immediate effects of the war, everyone on the Earth would ultimately be affected profoundly.

Aquatic Ecosystems

Aquatic organisms tend to be buffered against dramatic fluctuations in air temperature by the thermal inertia of water. Nevertheless, many freshwater systems would freeze to considerable depths or completely because of the climatic changes after a nuclear war. The effect of prolonged darkness on marine organisms has been estimated (*36*). Primary producers at the base of the marine food chain are particularly sensitive to prolonged low light levels; higher trophic levels are subject to lesser, delayed propagated effects. Moreover, the near-surface productivity of marine plankton is depressed significantly by present UV-B levels; even small increases in UV-B could have profound consequences for the structure of marine food chains (*16, 37*). It is often thought that the ocean margins would be a major source of sustenance of survivors of a nuclear war; the combined effects of darkness, UV-B, coastal storms, destruction of ships in the war, and concentration of radionuclides in shallow marine systems, however, cast strong doubt on this.

Conclusions

The predictions of climatic changes are quite robust (*4, 5*), so that qualitatively the same types of stresses would ensue from a limited war of 500 MT or less in which cities were targeted (*38*) as from a larger scale nuclear war of 10,000 MT. Essentially, all ecosystem support services would be severely impaired (Tables 2 and 3). We emphasize that survivors, at least in the Northern Hemisphere, would face extreme cold, water shortages, lack of food and fuel, heavy burdens of radiation and pollutants, disease, and severe psychological stress—all in twilight or darkness.

The possibility exists that the darkened skies and low temperatures would spread over the entire planet (*4, 5*). Should this occur, a severe extinction event could ensue, leaving a highly modified and biologically depauperate Earth. Species extinction could be expected for most tropical plants and animals, and for most terrestrial vertebrates of north temperate regions, a large number of plants, and numerous freshwater and some marine organisms.

It seems unlikely, however, that even in these circumstances *Homo sapiens* would be forced to extinction immediately. Whether any people would be able to persist for long in the face of highly modified biological communities; novel climates; high levels of radiation; shattered agricultural, social, and economic systems; extraordinary psychological stresses; and a host of other difficulties is open to question. It is clear that the ecosystem effects *alone* resulting from a large-scale thermonuclear war could be enough to destroy the current civilization in at least the Northern Hemisphere. Coupled with the direct casualties of over 1 billion people, the combined intermediate and long-term effects of nuclear war suggest that eventually there might be no human survivors in the Northern Hemisphere. Furthermore, the scenario described here is by no means the most severe that could be imagined with present world nuclear arsenals and those contemplated for the near future (*4, 5*). In any large-scale nuclear exchange between the superpowers, global environmental changes sufficient to cause the extinction of a major fraction of the plant and animal species on the Earth are likely. In that event, the possibility of the extinction of *Homo sapiens* cannot be excluded.

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Snow and ice feedbacks prolong effects of nuclear winter

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Recent studies using climate models[1–6] have suggested that drastic surface cooling (the "nuclear winter"[1]) caused by smoke and dust would follow a large-scale nuclear war, with possible drastic effects on the biosphere[7]. None of these studies looked at the long-term effects of time of year on the results. Moreover, although the general circulation model experiments of Covey *et al.*[4] had snow/albedo feedback on land, none of the experiments considered long-term seasonal cryospheric interactions with the forcing, especially the sea ice/thermal inertia feedback[8]. Although, in the previous studies, the presumed transport of smoke and dust to the Southern Hemisphere was mentioned, no detailed investigation of its effects has been made. I investigate here the interactions of snow and sea ice with the forcing, and look at the effects over a period of several years for a variety of strengths of the forcing and latitudinal distribution of the nuclear smoke and dust, including Southern Hemisphere injection. The seasonal dependence of both the forcing and the response are also investigated. Previous results are supported and possible longer lasting effects are revealed. The considerable uncertainties that remain are discussed.

The experiments were conducted with a seasonal energy balance climate model based on that of Sellers[9,10]. This model, described in detail elsewhere[8], has been used to simulate the effects of volcanic eruptions[11–14] and several other forcings[14,15] on climate. It uses 15-day time steps and solves for surface air temperature over land and water separately, in 10° latitude bands. Incoming and outgoing radiation are considered in detail and horizontal energy transports by the atmosphere and ocean are parameterized. Although energy balance climate models successfully reproduce mean properties of the observed climate system, details which may be important for the nuclear winter problem cannot be considered explicitly. Variations of atmospheric lapse rate, such as surface inversions, cannot be modelled. The three-dimensional circulation of the atmosphere, and its response to, and interaction with, the smoke and dust must be externally specified in this experiment, rather than internally calculated. The simple ocean model, with fixed mixed layer depth (from 90 m at the Equator to 40 m at the poles) and diffusive heat transport, prevents detailed consideration of ocean dynamical response. This climate model has the advantage, however, that it can be run rapidly on the computer and considers snow and ice feedbacks explicitly. The experiments reported here must, therefore, be interpreted as indicative of possible long-term interactions with the climate system that may result from forcing by nuclear smoke and dust. The exact surface-temperature responses would be different if the above details were included in a more complex model.

This climate model represents an energy balance for the vertically integrated surface–atmosphere system. In this experiment, the model is used to simulate the climate system beneath the nuclear smoke and dust layer. Turco *et al.*'s calculations[1] of the solar-energy flux at the ground for different scenarios were used to force the model. The scenarios of Turco *et al.* were first extrapolated to 400 days where the reduction of solar radiation went to zero for all cases. To force the model, the solar flux at each latitude band where there was smoke and dust was reduced by the same percentage for the particular scenario as given in their Fig. 4. Because Turco *et al.*'s values were for smoke and dust spread evenly over the Northern Hemisphere, they were adjusted according to the formula:

$$T^* = T^f$$

where T^* is the per cent transmission of solar radiation actually used as forcing, T is the per cent transmission from ref. 1, and f is a latitudinal factor equal to the reciprocal of the percentage of the Earth covered by the smoke in units of Northern Hemisphere area. The equation was derived by considering that solar flux reduction is due to an exponential decrease in radiation for a linear increase in smoke amount. The values of f are given in Table 1 for the different cases used here.

Table 1 Forcing variations of the experiments

Time dependence of the forcing			
Reduction of insolation according to Turco *et al.*[1] (their Fig. 4)			
Case			
1	5,000 MT–baseline		
14	100 MT–city attack		
17	10,000 MT–severe		
Latitudinal dependence of forcing			f
Ref. 4	30–70° N		2.273
Ref. 3	10–90° N		1.205
Global	90° S–90° N		0.500
Gradual Southern Hemisphere (SH)	10–90° N		1.205
	0–90° N	(after 3 months)	0.667
	0–90° S	(after 3 months)	0.333
Time war begins	**Control case**		
Winter (1 January)	Ref. 4 (30–70° N), $f = 2.273$		
Spring (1 April)	Ref. 1 5,000 MT–baseline (case 1)		
Summer (1 July)	Summer (war begins 1 July)		
Autumn (1 October)			

All other components of the climate model were not changed, including the outgoing long-wave radiation. This way of forcing the model implies that the smoke and dust layer is high in the atmosphere where it has little impact on the long-wave radiation, due to its particle size distribution. The long lifetime of the smoke in the upper troposphere follows from the results of MacCracken[2] and Turco *et al.*[1] that convection is essentially cut off due to the extreme solar absorption by the smoke. The results that follow depend on these assumptions.

Table 1 also summarizes the forcings used in these experiments. Three of Turco *et al.*'s scenarios were used for the time dependence of the forcing, case 1 (5,000 MT–baseline), case 14 (100 MT–city attack) and case 17 (10,000 MT–severe). These scenarios do not necessarily represent the most realistic or most probable radiative forcings, but were chosen to allow the climate model to assess the importance of feedbacks on the long-term response. The effects of the time of initiation of the war were tested by starting the forcing in four different seasons. Four different latitudinal distributions were used, two to correspond to previous GCM experiments, from ref. 4 (30° N–70° N uniformly distributed) and from ref. 3 (10° N–90° N uniformly distributed), a globally uniform case as an extreme limit, and a case called Gradual Southern Hemisphere where the smoke spreads gradually to the Southern Hemisphere after 3 months. This last case tests the suggestions of previous models that a cross-equatorial circulation would develop due to the large temperature gradient caused by the smoke which would then transport the smoke to the Southern Hemisphere even if no bombs were exploded there.

Because of the many different possible combinations of forcings that could have been used, it was decided to perform a control case, and then change one factor at a time from this. The control case chosen used Turco *et al.*'s 5,000 MT–baseline scenario (their case 1) and Covey *et al.*'s[4] latitude distribution (30° N–70° N), with the war beginning in summer.

Nine different runs were made. They are listed in Table 2 and the changes in surface temperature from the pre-war values are plotted in Fig. 1 as a function of latitude and time of year. Only the first 4 yr of results are shown. After this time, the temperature response shows a slow oscillation with the same pattern as in year 4 as the effect gradually diminishes. The same behaviour

Table 2 List of results shown in Fig. 1 and maximum cooling produced

Run	Latitudinal dependence	Time dependence	Time war begins	Results shown for:	Maximum temperature change (°C)
1a	Ref. 4	Ref. 1 Case 1 (baseline)	Summer	Land (control)	−21.4
1b	Ref. 4	Ref. 1 Case 1	Summer	Ocean	−10.7
1c	Ref. 4	Ref. 1 Case 1	Summer	Zonal average	−15.4
2	Ref. 4	Ref. 1 Case 1	Autumn	Land	−8.3
3	Ref. 4	Ref. 1 Case 1	Winter	Land	−8.1
4	Ref. 4	Ref. 1 Case 1	Spring	Land	−16.9
5	Ref. 3	Ref. 1 Case 1	Summer	Land	−21.1
6	Gradual Southern Hemisphere (SH)	Ref. 1 Case 1	Summer	Land	−19.4
7	Global	Ref. 1 Case 1	Summer	Land	−18.3
8	Ref. 4	Ref. 1 Case 17 (10,000 MT–severe)	Summer	Land	−22.9 (year 2) −16.4
9	Ref. 4	Ref. 1 Case 14 (100 MT–city)	Summer	Land	−19.3

can be seen in response to forcing from volcanic eruptions both for a 9-yr climate model simulation[11,12] and in surface temperature observations for the past 90 yr (ref. 16).

Results 1a, 1b and 1c (Table 2) are all from the same control run, and present the surface-air temperature change for land grid areas, ocean grid areas and the zonal average. The effect is initially much larger over land, due to the lower thermal inertia. The maximum cooling is 21.4° C and occurs in the 50–60° N latitude band 45–60 days after the beginning of the war. The Northern Hemisphere average land cooling at this time is 11.5° C, which agrees well with MacCracken[2]. Over the ocean grid boxes, the maximum effect is delayed and smaller, but occurs in the northernmost grid box, due to lower thermal inertia here caused by the presence of sea ice, and has a value of 10.7° C 90–105 days after the war starts. Even in the mid-latitude ocean areas, large temperature drops are found, which have not been found in any of the previous studies. A much more detailed ocean model than the mixed layer with fixed depth and diffusive heat transport used here is needed to investigate these effects further. The zonal average maximum effect of 15.4° C agrees almost exactly with MacCracken's results, as does the land value with the other previous results.

The climate model response in the first year after the war begins can be easily understood as a linear response to decreased insolation. During the second year, as the forcing disappears, the nonlinear effects of the snow and ice feedbacks become apparent. The large area of cooling of more than 5 °C found in the mid and high latitudes in the summer over land is due to the snow/albedo feedback. The additional snow produced due to the large previous cooling reflects more solar radiation, enhancing the cooling. This feedback is only important in the summer when there is substantial insolation[8]. Over the ocean, the largest cooling in the second year is at the poles in the winter. This pattern, produced by the sea ice/thermal inertia feedback[8], is caused by the enhanced amplitude of the seasonal cycle of temperature. This occurs when cooling produces more sea ice which lowers the thermal inertia of the ocean. The sea ice/albedo feedback, which in the absence of the thermal inertia feedback would produce the same pattern that the snow/albedo feedback produces on land, with enhanced sensitivity in the summer, is completely overwhelmed by the much stronger thermal inertia feedback over the ocean. (The feedbacks discussed here ignore possible effects of smoke particles settling on the snow and ice and hence lowering the albedo until the next snowfall[17]. These dirty snow effects may weaken, or even enhance, these feedbacks.)

The mixture of these two feedbacks from land and ocean can be seen in the pattern of the zonal average for the second year. The overall pattern over land begins to resemble the ocean pattern at the end of the second year, as the ocean effects dominate due to the horizontal mixing. In the third year, only a small area of sensitivity is evident in the summer high latitudes over land from the snow/albedo feedback. By the end of the second year, 18 months after the start of the war, cooling over the oceans is of the same amplitude as over land, and after that it is even larger, as the ocean thermal inertia slows the recovery to pre-war temperatures. Note that these feedbacks and patterns are also evident in the equilibrium response of the climate model to external forcing, such as changing solar constant or CO_2 (refs 8, 18), as opposed to the transient response shown here.

Because of the cryosphere feedbacks discussed above, the response of the climate to nuclear war is longer and larger than previously found by Turco *et al.*[1] who did not include these feedbacks. It would presumably be very difficult to grow crops not only in the summer of the year that the war began, but also in the summer of the next year, with temperatures over land almost 6 °C (>10 °F) colder than normal.

Several other experiments were conducted to test the effects of time of year that the war begins, latitudinal spread of the smoke, and strength of the forcing. To save space, only the response over land is shown for comparison with the control case. The response over land is probably of more interest anyway, because it is larger than the first year response over the sea, and humans and agriculture are affected. The relative effects over the ocean, as shown for the control, are the same for all these cases.

Runs 2, 3 and 4 tested the effects of beginning the war in autumn, winter and spring. As can be seen in Fig. 1, the effects in the autumn and winter cases are not as large as in the control. This is because there is less insolation at the time of the maximum atmospheric loading from smoke and dust, and, therefore, less absolute reduction of incoming energy. In the autumn case, the initial effect is larger than the largest effect for the winter case, but it occurs in the autumn and does not last as long. The cooling during the following summer, however, is more than 4 °C during the entire summer from 40° N to the Pole. In the winter case, although the initial effect is small, enough smoke remains to cause a large effect the following summer, with a cooling as large as 8 °C. This effect was not seen by Covey *et al.*[4] because they ran their winter experiment for only 20 days. The spring case is quite similar to the summer case with large cooling during the first summer, and substantial, although not quite as large, cooling during the second summer.

Runs 5, 6 and 7 illustrate the effects of spreading the nuclear smoke and dust over a greater latitudinal extent. In the Aleksandrov–Stenchikov[3] case (run 5), the results are almost the same as the control case, but the cooling extends over more latitudes and persists at a slightly larger amplitude in the years after the war. Although the smoke concentration is lower in this case than in the control, there is still so much smoke that almost all of the sunlight is initially prevented from reaching the ground. (The small regions of enhanced or decreased sensitivity found in the tropics in this and the following runs are due to a small model instability relating to its inability to calculate the circulation correctly under such extreme forcing. They are not real, and a slight smoothing would produce a more realistic response.)

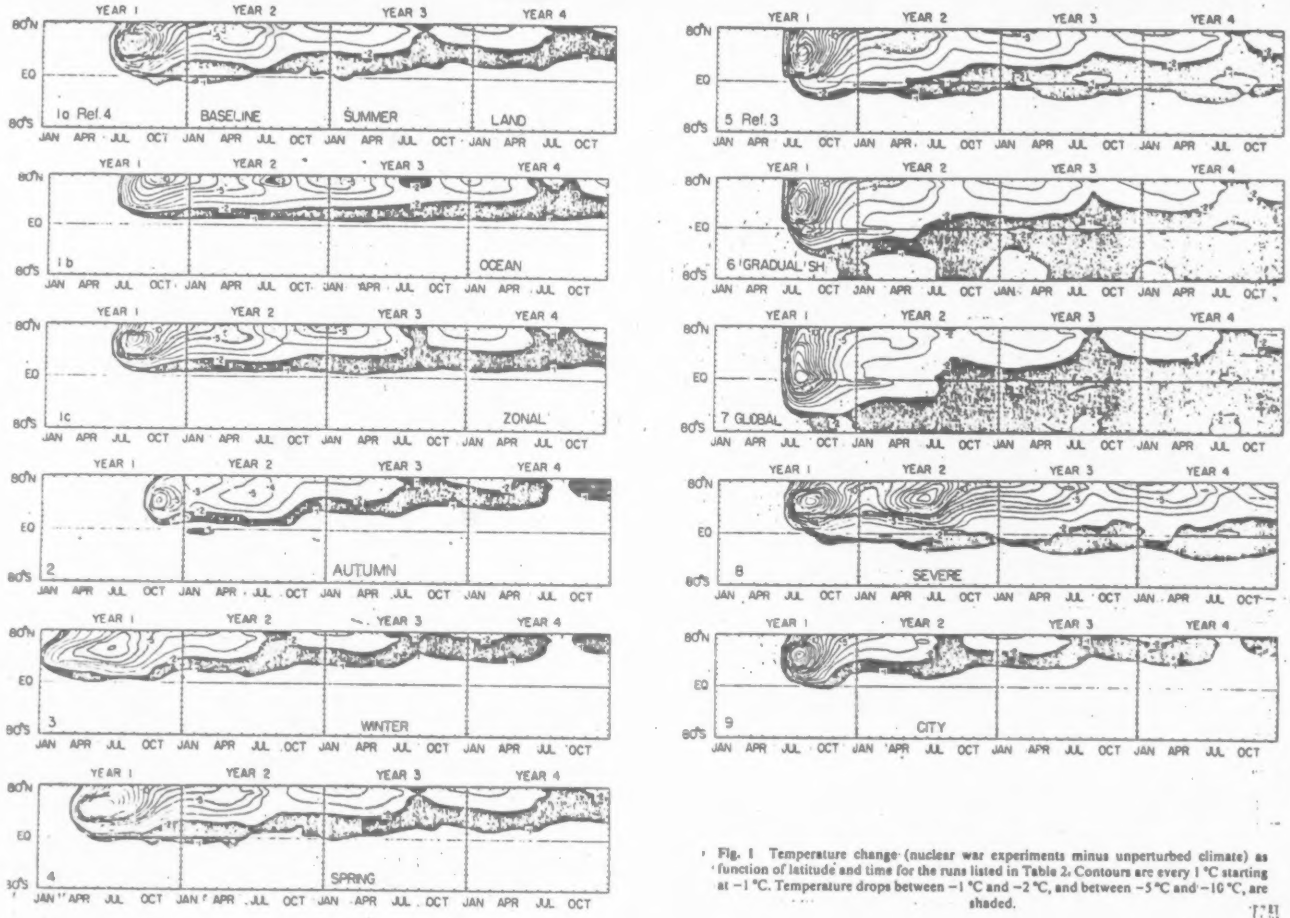

Fig. 1 Temperature change (nuclear war experiments minus unperturbed climate) as function of latitude and time for the runs listed in Table 2. Contours are every 1 °C starting at −1 °C. Temperature drops between −1 °C and −2 °C, and between −5 °C and −10 °C, are shaded.

In the Gradual Southern Hemisphere case (run 6), the Northern Hemisphere response is again about the same as in the control. Although the response is slightly less in year 2, it is larger in years 3 and 4 because the forcing at lower latitudes makes the effects last longer through ocean cooling. In this case, we see maximum cooling of about 8 °C in the tropics, and much smaller cooling in the Southern Hemisphere. The smaller Southern Hemisphere effect is caused by the much larger thermal inertia due to the much larger percentage of oceans in this hemisphere, as well as the lack of land in the high mid-latitudes on which to produce a snow/albedo feedback. This effect is illustrated in run 7, where the forcing is the same at all latitudes, but the response is much less in the Southern Hemisphere. This is partly because the forcing started in Southern Hemisphere winter. A global run starting in Southern Hemisphere summer (not shown here) produced about the same response in the Southern as in the Northern Hemisphere. The larger Southern Hemisphere thermal inertia almost exactly compensated for the larger forcing.

The effects of using the severe 10,000 MT forcing[1] are shown in run 8. The results during the first year are virtually the same as in the control case, with the maximum cooling not even 2 °C larger. The dramatic difference comes in the second year, where the snow/albedo feedback produces a cooling of more than 16 °C during the summer 1 yr after the war begins. The effects persist for several years after this, with year 4 in this case resembling year 2 in the control case. Although this result is almost a 'worst case' scenario (more latitudinal spread would make it even worse), it should receive serious consideration[1] because it is plausible. Run 9 shows that even the smaller 100 MT–city attack can have virtually the same effects as the control case, in agreement with Turco *et al*[1].

These experiments show that the climatic effects of a nuclear war might persist longer than previously calculated. The use of a model which includes snow and ice feedbacks and ocean response shows that the effects can be large even 1 yr after the war begins. Latitudinal spread of the nuclear smoke and dust can produce large cooling in the tropics where life is more sensitive to cooling due to the absence of a natural seasonal cycle[7], but the cooling there is not as large as would be expected from a global average model.

The results presented here must be considered as preliminary, since the climate model used cannot consider many of the complex interactions that might result. These include the dynamical and radiative interactions between the atmospheric circulation and the smoke, the possibly patchy nature of the smoke distribution, long-wave radiative interactions, ocean circulation and mixed-layer depth responses, atmospheric hydrological cycle responses (including changes in cloudiness and changes in washout rates due to changes in precipitation), the effects of considering diurnal solar forcing (R. Cess, personal communication), and the effects of placing dust over the smoke rather than having them evenly mixed[19]. What the initial distribution of smoke and dust would be is also not well known and depends on untested assumptions about numbers and sizes of fires, number of particles produced per fire, initial rainout and washout, particle size distribution and coagulation rates, vertical distribution, targeting strategies and initial weather conditions. All these processes must be included to produce realistic results. In the absence of proof that these assumptions would drastically change the results, the prospect of a nuclear winter following virtually any scenario for a nuclear war must be taken very seriously.

This work has been supported by NSF grant ATM-8213184. I thank S. Schneider, P. M. Kelly and S. Warren for valuable comments, the NASA Goddard Laboratory for Atmospheric Sciences for computer time on the Amdahl V6, and Chuck Mulchi and Patricia Palasik for drawing the figure.

Received 2 April; accepted 26 June 1984.

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Worldwide marine temperature fluctuations 1856–1981

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Paltridge and Woodruff[1] found a warming of global mean sea-surface temperatures (SSTs) of ~1 °C in the first half of the present century, but there are doubts about its reality because spurious temperature fluctuations can arise from changes in measuring instruments[2,3] and because inter-annual fluctuations may contain sufficient variance to allow the observed inter-decadal variations to fall within the limits of sampling error of a stationary series[3]. We present here the results of analyses of worldwide SSTs and night near-surface marine air temperature (MAT) for the period 1856–1981 with the aim of estimating the magnitudes of recent climatic fluctuations of temperature at the ocean surface, taking account of changes in observing procedures. Our results show a worldwide temperature fluctuation of range ≃0.6 °C (in broad agreement with a preliminary analysis of global SST[2]), with the coldest period being centred around 1905–10 and the warmest occurring in the 1940s. The fluctuation has a similar magnitude to, and is nearly in phase with, climatic warmings and coolings near the surface of the Northern Hemisphere land masses for the period after 1900. Before 1900 the trends are sharply different.

The data (46 million non-duplicated SST data and 24 million non-duplicated night MAT data) were derived from the Meteorological Office Main Marine Data Bank[4]. Observations departing from the whole-period normal by more than ±6 °C for SST and ±10 °C for MAT were rejected. Relaxation of the limits for SST to ±9 °C had little effect even in areas of high natural variability. The observations were composited into

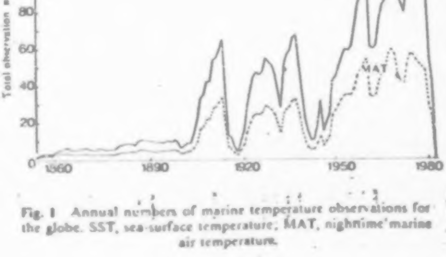

Fig. 1 Annual numbers of marine temperature observations for the globe. SST, sea-surface temperature; MAT, nighttime marine air temperature.

APPENDIX II

QUESTIONS AND ANSWERS SUBMITTED FOR THE RECORD

ANSWERS TO QUESTIONS

Dr. Alan Hecht, Director
National Climate Program Office
National Oceanic and Atmospheric Administration
Washington, D. C.

Responses to questions from House Committee on Science and Technology

1a. "To what extent has nuclear winter research been conducted in other countries?

The only country besides the U.S. which has done substantial work on the issue of "nuclear winter" has been the Soviet Union. That work has been primarily centered around the USSR Academy of Science's climate model results using nuclear explosion scenarios similar to those in the TTAPS report. These results have been published. Contacts with Sovier scientists involved with these studies show that they are aware of the major uncertainties in the "nuclear winter" hypothesis (i.e. pertaining to fire phenomenology and climate modeling).

Paul Crutzen from the Federal Republic of Germany has done work on the "nuclear winter" issue, but as an individual scientist.

1b. "What plans does the U.S. have for promoting joint research with the USSR and with other countries?"

No definite plans to conduct joint research have been made between the U.S. and any other country. At this stage, preliminary contacts have been made with the USSR (specifically the USSR Academy of Sciences), with Canada (for joint fire research), and the countries participating in the series of meetings at Erice, Italy. The advantages/disadvantages to conducting joint research on this issue are presently being discussed between the federal agencies involved.

1c. "What coordination efforts will there be to tie in your program with international programs?"

2a. "To what extent will it respond to the uncertainties and gaps in the TTAPS and other studies?"

2b. "To what extent and at what time will biological consequences be addressed?

2d. "What uncertainties about nuclear winter will remain unresolved, even after your 5-year study?"

(Answer: 1c, 2a, 2b, 2d:)

The Administration is considering a number of options for investigating the nuclear winter hypothesis. Details on international cooperation, scope relative to TTAPS, inclusion of biological studies, and potential for resolving uncertainties are being determined.

2c. "Will the research plan be made available for broad public review prior to its implementation?"

After the Administration has obtained interagency agreement on these studies, information will be made available to the public (subject to national security requirements).

Dr. Leon Goure, Director
Center for Soviet Studies
Science Applications International Corp.

QUESTION: In some respects, the nuclear winter issue has reinforced the uncertainties regarding potential consequences of nuclear war.

a. Is the issue decisive enough to be incorporated into strategic policy planning?

b. How much certainty is needed before nuclear winter is factored into strategic planning?

At the present time, the nuclear winter hypothesis is fraught with so many uncertainties concerning the key parameters which are claimed may cause some sort of nuclear winter effect and the assumptions about nuclear exchange scenarios, that it would be premature to incorporate this issue into actual U.S. strategic planning. However, if subsequent research were to confirm the likelihood that a severe climatic effect may occur as a consequence of certain types of nuclear exchange scenarios, then in all probability this factor would need to be considered by strategic planners. Potentially, the nuclear winter issue may have significant bearing on strategic planning—in particular, on strategic deterrence, weapon design and employment concepts, the size of the strategic forces, targeting, strategic defense, war survival measures, and undoubtedly also arms control policies.

Strategic policy planning is a complex process, and significant changes in it require well-founded rationales. Account must be taken not only of U.S. objectives, but also of Soviet objectives and strategic doctrine. In themselves, uncertainties regarding potential consequences of a nuclear war may be seen as reinforcing U.S. strategic deterrence policy, even while they may adversely affect a warfighting doctrine and strategy such as that of the Soviet Union. It is doubtful that further research will be able to fully resolve all uncertainties about potential consequences of nuclear war, including its possible nuclear winter effects. It should be possible, however, for further research to determine—with far greater certainty than is presently the case—whether or not severe climatic perturbations are likely to occur in connection with various nuclear exchange scenarios. If, at some point, it is determined that severe climatic effects are likely to occur, it would be reasonable to factor this finding and its implications into strategic planning and U.S. deterrence policy.

Precisely because of the complexities of strategic planning and the difficulties of changing existing concepts and postures, it would be desirable to begin the examination of the possible strategic implications of nuclear winter on a contingency basis, simultaneously with the research program to assess the key parameters of the nuclear winter hypothesis. At the same time, it would be important to continuously analyze not only Soviet research on the nuclear winter phenomenon but, especially, indications of any influence this may have on Soviet strategic doctrine and weapons programs.

QUESTION: What are the implications for civil defense and civil preparedness plans?

The nuclear winter issue does not negate the utility of civil defense and civil preparedness planning and preparations. There is no doubt that large and potentially catastrophic population losses from the viewpoint of national survival could occur in the event of a nuclear war as a direct result of the effects of nuclear detonations and radioactive fallout. Consequently, the protection of the population and critical resources against the immediate and secondary effects of nuclear detonations is an important requirement for national survival as long as a threat of nuclear war exists. Without the survival of the greater part of the country's population from these effects of nuclear detonations, the nuclear winter factor may be of relatively little significance from the standpoint of the country subjected to a nuclear attack.

The approach to population protection planning, however, under conditions of a nuclear winter threat may be altered if it were to lead both the United States and the Soviet Union to adopt a city-avoidance strategy. In such a case, population losses from the prompt effects of nuclear detonations would be significantly smaller and protection of the urban population—primarily against radioactive fallout—could be done in-place, i.e., in shelters, rather than rely on the population's pre-attack evacuation and dispersal. In any case, civil defense preparedness plans and measures should include preparations for sustaining the surviving population during the post-attack period.

QUESTION: What precautions could the U.S. take to mitigate the consequences of nuclear winter?

Given that the severity of possible climatic effects, their duration, and environmental impact are at present uncertain, it is diffuclt to predict all the preparations which may be needed to mitigate the consequences of a nuclear winter. Some measures, especially as they relate to the feeding and medical care of the surviving population and preservation of essential transportation following an attack, would be essentially the same whether or not there is a nuclear winter effect. There are sufficient food stocks in the United States outside the likely targets for enemy strikes to feed the population for one or more years. It would be desirable, however, that food, medical and fuel stocks be located in planned areas of concentration of the surviving population to minimize transportation requirements. It may also be necessary to store there standby electric power generators to ensure the operations of critical medical, food processing and other facilities in an emergency. Similarly there should be stocks of decontamination equipment.

The nuclear winter effect could pose several additional problems, especially in the matter of heating and water supply during a possible protracted period of subfreezing temperatures. Heating would probably depend on the availability of fossil fuel and wood, and in the case of buildings using oil burning or electric heating systems, the substitution for them of coal or wood-burning stoves. Such substitutions were extensively practiced in European countries during World War II. A certain amount of pre-stocking of such fuels and essential equipment would be desirable in planned areas of concentration of the population to reduce initial transportation requirements, especially in fuel deficient regions. In the matter of assuring the water supply, this will depend on the character of local water systems and water sources. Because of the disruption of electric power in the event of a nuclear war, the water systems should be provided in any event with standby generators and fuel stocks. Some measures to protect the water supply system would have to be taken where such systems are likely to be rendered inoperative by protracted subfreezing temperatures, which may be especially the case in the southern regions of the country where they are not designed for such temperatures.

Overall, it would appear at the present time that while measures to mitigate the consquences of a nuclear winter would add to the scope and cost of war survival preparations, the problem appears to be susceptible to effective practical solutions. After all, survival in subfreezing temperatures for protracted periods of time is a normal condition in many parts of the world, including parts of the United States, and has been dealt with for many centuries. Under nuclear war conditions, this requires appropriate planning and preparations which take into account the probable environment and conditions following an attack. It is by no means a foregone conclusion that the post-attack environment would be as apocalyptic as some people claim, but it certainly could be catastrophic in the absence of civil defense and preparatory measures to protect the population and sustain it following an attack.

QUESTION: What attention has been given to the nuclear winter findings in the Soviet Union? Are the policy implications—including strategic doctrine, arms control, and civil defense—being addressed within the Soviet government? Have government officials been briefed on these issues by members of the scientific community? At what levels and by whom?

Soviet science spokesmen and publications persistently claim that Soviet scientists have independently confirmed the nuclear winter hypothesis. In actual fact this is not the case. As far as is publicly known, Soviet scientists have addressed the nuclear winter hypothesis only to a very limited extent. Soviet scientists have not produced any independent data on the key parameters of the nuclear winter hypothesis, nor any independent scenarios. Instead, as they publicly acknowledge, they have simply incorporated the worst-case estimates and scenarios of the TTAPS study and have applied these to two models of global atmospheric circulation. The most widely publicized of these models in the West is one by V.V. Aleksandrov and G. Stenchikov of the Computation Center of the USSR Academy of Sciences. This model is based on an adaptation of the Mintz-Arakawa Atmospheric Circulation Model published by the RAND Corporation (Santa Monica, California) in 1971, and is considered to be severely flawed by American scientists. The other circulation model by G.S. Golitsyn and A.S. Ginzberg of the Institute of Atmospheric Physics of the USSR Academy of Sciences is derived from studies of Martian dust storms. It too is considered to be seriously flawed. Beyond this, as Dr. R.P. Turco, a primary contributor to the TTAPS study has recently noted, Soviet scientists have produced no substantive data and, as he says, little evidence of objective scientific analysis.

An examination of Soviet publications and of statements at international conferences on the nuclear winter hypothesis leaves little doubt that the Soviets have seen this hypothesis primarily as a propaganda opportunity to influence world public opinion in support of Soviet arms control proposals and in opposition to U.S. defense programs. The role of Soviet scientists as propagandists for this purpose is frequently cited in Soviet publications. The TTAPS study has not been published in the Soviet Union and public discussion of the nuclear winter hypothesis in the Soviet mass media has been sparce. Most of the published statements and broadcasts dealing with this subject have been addressed to foreign audiences.

The only policy implication of nuclear winter cited by Soviet sources is the necessity to prevent a nuclear war and, consequently, the need for the United States to agree to all Soviet arms control proposals. There is no public indication that the possibility of a nuclear winter effect has in any way influenced current Soviet strategic doctrine or civil defense planning. There are no indications of any changes in the further buildup of Soviet strategic weapons, targeting doctrine or weapon employment concepts because of concern over a possible nuclear winter effect. As to civil defense, a Radio Moscow broadcast on April 24, 1984, while noting that many scientists are predicting the destruction of civilization in the event of a nuclear war, stated that the Soviet Union is continuing to strengthen its civil defense, build shelters, and instruct the population in protective measures. The broadcast asserted that in the face of the alleged threat from the West, the Soviet Union must protect its population and that "this requires not only armed forces that would stand up to such aggression, but an effective system of civil defense as well."

Whether Soviet scientists have briefed Soviet political and military leaders on the nuclear winter issue is not known. Probably this has been done at some level because the Soviet nuclear winter propaganda campaign aimed at the West naturally requires high level approval. It should be noted, however, that the marching orders given to Soviet scientists by the leadership do not reflect concern for the strategic implications of nuclear winter. For example, in an address to the members of the USSR Academy of Sciences on March 14, 1984, the Academy's president, A.P. Aleksandrov, while noting that a nuclear war may result in the death of mankind, instructed the assembled scientists to work on "promoting the development of defense technology that would make an attack on our country unacceptable." Of course, the Soviet government may be conducting a secret program of research on nuclear winter, but, even if this is the case, it is doubtful that it has as yet reached any definitive conclusions concerning its strategic implications.

QUESTION: In the final paragraphs of your prepared testimony you draw a distinction between the Soviets' "propaganda" stance of support for the TTAPS hypothesis and their build-up of nuclear weapons. How does this dichotomy differ from an apparently similar dichotomy in the U.S.—namely, a commitment to a multi-million dollar research project on nuclear winter and an accelerated purchase of nuclear arms?

First of all, it should be noted that the TTAPS study is a private one, conducted by a number of private individuals and that it has not been endorsed or confirmed by the U.S. government. In the case of the Soviet Union, the scientists who claim to independently confirm the TTAPS findings are officials, part of the Soviet government's science organization, and reporting their findings to the government and its leadership elements. Both the president of the USSR Academy of Sciences, A.P. Aleksandrov, and the vice-president, Ye.P. Velikhov, a frequent spokesman in support of the nuclear winter hypothesis, have direct access to Soviet political and military leaders. Indeed, any serious research on the nuclear winter issue, as all research with military implications, would be carried out at the Academy and its member institutes under military control. In principle, therefore, Soviet nuclear winter findings, if taken seriously by the leadership, could be very quickly reflected in Soviet weapons programs. It is noteworthy, however, that in his May 9, 1984, article in Red Star, the former chief of the Soviet General Staff, Marshal of the Soviet Union N.V. Ogarkov, asserted that while both the United States and Soviet Union already possess sufficient weapons to destroy all important targets in both countries, "the buildup is continuing." Furthermore, Ogarkov rejected out of hand any possibility of a "limited" nuclear war, predicting instead that in the event of a conflict, the entire Soviet nuclear arsenal would be used—hardly a statement reflecting concern over a possible nuclear winter effect which, incidentally, he has never mentioned in his public statements.

Finally, while the United States is committed to a multi-million dollar comprehensive research effort on nuclear winter, there is no actual evidence of a similar effort being undertaken in the Soviet Union. Velikhov's private statement to Dr. Sagan concerning a large Soviet research effort must be viewed with considerable skepticism. American scientists in contact with Soviet scientists on questions relating to the study of nuclear winter have found no indications to date of an actual major Soviet research effort, of cooperation for this purpose among various Soviet institutes, or of the organization of a significant experiment program to objectively analyze the various uncertainties which Soviet scientists acknowledge to exist in connection with the nuclear winter hypothesis. If a classified effort of this sort is under way, the West is unlikely to learn much about it or its findings.

QUESTION: What is your opinion on the idea of a treaty to ban the targeting of cities or installations co-located with cities?

The concept of an agreement on city-avoidance has been repeatedly raised in the United States. While an agreement on city-avoidance would appear to be desirable in principle, it should be recognized that it would pose a number of serious problems. First, such a treaty is not enforceable. Second, it may significantly weaken deterrence, which, after all, is largely based on the threat of destruction of economic targets and the associated death of large numbers of civilians. Third, to be meaningful, the treaty must require the cities to be "open," that is, to not contain any facilities which would support a war effort. Otherwise, the treaty could be used to shield military capabilities which could be deliberately placed in the cities to ensure their immunity from attack. Consequently, the treaty would have to have provisions for mutual inspection and verification. All this may greatly inhibit the attainment of such a treaty.

It should be noted that so far the Soviets have persistently rejected all U.S. proposals or suggestions for an agreement on banning strikes on cities, claiming that the United States is thereby seeking to gain an advantage for its first counterforce strike by ensuring its survival from Soviet retaliatory strikes and depriving the Soviet Union of effective deterrence. It is possible that in the event of a confirmation of a severe nuclear winter effect as a result of strikes on cities, the Soviet Union may change its position on this question. However, it may also choose not to do so, preferring instead to use the threat of strikes on urban areas and of causing a possible nuclear winter effect for coercive purposes. In any event, the question of a treaty banning the targeting of cities and its implications requires careful examination and analysis before it can be given serious consideration.

T. A. Postol **QUESTION 1**

1. In some respects, the nuclear winter issue has reinforced the uncertainties regarding potential consequences of nuclear war.
    a. Is the issue decisive enough to be incorporated into strategic policy planning?
    b. How much certainty is needed before nuclear winter is factored into strategic planning.

Answer to 1A **(Page 1 of 2 Pages)**

At this time, the physics of the nuclear winter effect is not very well understood, and as I have noted in my earlier testimony, even if the effect were well understood, our current nuclear policy contains so many inconsistencies and contradictions that incorporating it into our planning policy will, at best, be a hit or miss process.

Since our current nuclear policy planning basically models nuclear warfare as a chess game between two reasoning informed adversaries, its conceptual foundation leads to guidance that places no emphasis on planning for uncertainty. Since the policy does not recognize the significance of uncertainty in military planning, it provides no sensible framework for accommodating the planning uncertainties that a possible nuclear winter effect will surely introduce. In fact, in my view, it doesn't even provide an adequate framework for today's planning.

However, I understand that the 1985 Defense Authorization Act directs the Secretary of Defense to study the possible implications of nuclear environmental effects, and the military and policy planning issues raised by such effects, with regard to "strategy, targeting, planning, command, control, procurement, and deployment."

Although the uncertainties associated with our current understanding of many nuclear environmental effects will, in my view, make it difficult or impossible to study many of the military planning issues that must eventually be addressed, there are still a wide variety of useful results that this study could produce. Furthermore, some of the more useful results could, and should be unclassified.

I would like to recommend that the Congress make sure that the classified addenda to that report contains at a minimum, a breakdown, at several levels of classification, of the fuel loadings around planned targets for all the different SIOP and NON-SIOP options. This would at least give us some idea which SIOP and NON-SIOP options might possibly induce a nuclear winter effect.

T. A. Postol QUESTION 1

Answer to 1A (Page 2 of 2 Pages)

A very detailed breakdown of this type would obviously require special access to extremely sensitive military information. However, in SIOP related studies, we routinely aggregate data so that many militarily sensitive details of war plans cannot be deduced from the data. Depending on the level of aggregation, revealing and useful data could certainly be made available to the Congress at the SECRET or TOP SECRET level.

In addition, at the unclassified level, a breakdown of the fuel loadings around areas of obvious potential targeting interest could be made available. A great deal of this information could be generated using non-militarily sensitive sources like LANDSAT data, and would be of enormous value for purposes of unclassified scientific investigations. Urban/industrial areas could be included, and high, low and mean estimates of fuel loadings could also be provided. The estimates based on LANDSAT data could be refined, at no risk to security, with qualitative information obtained from moderate resolution reconnaissance data. Many of the artists drawings in the 1983 and 1984 DoD publications, Soviet Military Power, could be viewed as a form of "aggregation of data," designed to protect sensitive technical details of intelligence gathering assets.

T. A. Postol QUESTION 1

1. In some respects, the nuclear winter issue has reinforced the uncertainties regarding potential consequences of nuclear war.

   a. Is the issue decisive enough to be incorporated into strategic policy planning?

   b. How much certainty is needed before nuclear winter is factored into strategic planning.

Answer to 1B

It is very difficult to say when the threat of a nuclear winter will be sufficiently certain that it will enter our nuclear planning for two reasons: first, the scale and nature of the uncertainties that have to be accommodated in planning may remain very large, even when we understand the physics of this phenomenon much better; and second, a decision to incorporate this kind of uncertainty into our planning will probably have to be made at the highest levels of our Government, probably at the Presidential level.

Unlike our current approach to Presidential directives on matters regarding issues of nuclear plans and policy, I would recommend that any Presidential guidance related to the nuclear winter issue provide detailed direction to our military planners, and a mechanism for review of its implementation be created.

For such guidance to be properly drafted, the involvement of individuals with a detailed technical understanding of nuclear planning, weapons effects, and the nuclear winter phenomenon would be required. My experience with the weapons laboratories, for instance, gives me high confidence that such expertise is available to the President. I would like to emphasize that a detailed knowledge of both nuclear planning and nuclear weapons effects is, in my view, mandatory, since these war plans are very complex, and serious planning oversights can be inadvertently missed, even by sophisticated technical people who are not familiar with current techniques. In fact, I would recommend that the above process be applied to all our nuclear planning.

2. Regarding the size and structure of current nuclear arsenals and the advanced weapons technologies being developed --

   a. How might the development of a "Star Wars" defense system affect the nature of a nuclear winter?
   b. Similarly, what would be the effects of advanced systems such as the MX.

Answer to 2A

At this time, I have no idea how to project whether or not an attempt to implement a "Star Wars" defense would result in an increased or decreased risk of a nuclear winter. There are many technically unresolved questions associated with these so called "Star Wars" technologies, many possible U.S.-Soviet actions and reactions, and many possible outcomes of a spiralling cycle of measures and countermeasures. There is simply no way to determine which of an infinite number of possible outcomes would result.

For example, if a "Star Wars" defense that is capable against today's Soviet threat were to be deployed, and the Soviets responded with a tremendous expansion of their arsenal, incorporating tens or hundreds of thousands of decoys to help penetrate the defense, the possibility of a nuclear winter from a determined attack might be considerably greater than it is today. On the other hand, if the defense could in fact intercept all attacking warheads (bomber and cruise missile along with ballistic missiles) and the Soviets could not, in desperation, smuggle a large number of suitcase bombs or other devices into the country, the threat of a nuclear winter might be diminished.

Since the question of whether or not the United States should develop and/or deploy a "Star Wars" defense has very far ranging implications for our national security, after I finish responding to the Committee's questions (see page 14 of this written statement) I would like to provide some additional comments on national planning issues raised by the President's initiative.

T. A. Postol QUESTION 2

2. Regarding the size and structure of current nuclear arsenals and the advanced weapons technologies being developed --

   a. How might the development of a "Star Wars" defense system affect the nature of a nuclear winter?

   b. Similarly, what would be the effects of advanced systems such as the MX.

Answer to 2B **(Page 1 of 2 Pages)**

The MX missile system is designed to deliver warheads with a sufficient yield/accuracy combination that even Soviet targets that are extremely "hard" to nuclear effects could be destroyed with high probability. A very large number of such targets could possibly, for instance, be missile silos.

Although many of these targets are no doubt in forested areas in European Russia and along the Trans-Siberian Railway, they are relatively distant from large urban/industrial areas.

At the moment, preliminary work on the nuclear winter effect seems to indicate that even very large areas of burning forest might not produce and inject sufficient smoke high into the atmosphere to cause severe temperature effects over the continents. If subsequent research continues to support this assessment, very large scale attacks against such isolated "hard" military targets would probably not result in a severe nuclear winter effect.

For reasons that are presented in the next paragraph, it is plausible to guess that MX, when and if it is deployed, will primarily be targeted against hard targets. If, in fact, most MX warheads were targeted against missile silos, or certain other relatively "hard" and physically isolated military targets, it seems probable that these warheads would not contribute significantly to the nuclear winter effect.

The reason why it is highly plausible that MX will be targeted mostly against hard targets is as follows:

Any scheme of optimized targeting will tend to match warheads of appropriate capability against targets with appropriate vulnerabilities. For example, if hard target capable warheads were to be used against soft targets, than fewer hard target warheads would be available for use against the harder targets. Although the remaining hard targets could still be attacked with less effective "soft" target capable warheads, the damage achieved per ground zero would be smaller. If instead, the relatively easy to destroy soft targets are attacked with soft target capable warheads, then many more hard target capable warheads would remain for use against hard targets. This fact of optimization theory, is why any informed military analyst would expect MX to be targeted almost exclusively against very hard targets.

T. A. Postol QUESTION 2

Answer to 2B (Page 2 of 2 Pages)

As noted in my earlier written testimony, one cannot yet reject the possibility that a less than severe nuclear winter effect, possibly induced by attacks against isolated hard military targets, might also have significant implications for policy and planning. If subsequent research on the nuclear winter effect produces such an unexpected result, the implications of such a finding would have to be assessed against all new nuclear systems. Since all these systems, the cruise missiles, bomber delivered gravity bombs, and the TRIDENT II will have hard target capability indistinguishable from that of MX, such a finding could have considerable implications for the entire modernization program.

T. A. Postol **QUESTION 3**

3. What precautions should the U.S. take, if any, to mitigate the consequences of nuclear winter.

Answer to 3

While I in no way wish to diminish the terrifying prospects of a nuclear winter, I do not feel we should draw any comfort from the possibility that a nuclear war might occur without a nuclear winter. For this reason, I would argue that we must focus on the more fundamental question: how do we prevent a nuclear war.

I would further argue that we must focus on those military planning and diplomatic efforts that appear most promising as a means towards this end.

In my response to question one, I have tried to point out why a poorly thought out national nuclear policy results in both a confused and contradictory set of national security objectives, as well as serious practical planning problems for our military. Therefore, a national policy aimed at clearly delineating our security objectives, that can be usefully used by both our military planners, and our diplomats in arms control talks, would be the most important first step in this direction.

T. A. Postol **QUESTION 4**

4. What attention has been given to the nuclear winter findings in the Soviet Union? Are the policy implications -- including strategic doctrine, arms control, and civil defense -- being addressed within the Soviet government? Have government officials been briefed on these issues by members of the scientific community? At what levels and by whom?

Answer to 4 **(Page 1 of 2 Pages)**

Unfortunately, I have not followed the Soviet work in this area very carefully, as I have primarily used my contacts at the National Academy of Sciences, Lawrence Livermore National Laboratory, Research and Development Associates, Cornell University, and Stanford University to keep abreast of scientific activities in this area.

Although it is impossible for me to surmise how much serious work is going on inside the Soviet Union, there is little doubt that some very distinguished Soviet scientists are giving this issue attention. Just recently, in fact, a group of scholars from the Stanford Center for International Security and Arms Control met with Sergei Kapitza in Moscow. Professor Kapitza, a very distinguished member of the Institute for Physical Problems in Moscow, briefed them on activities of the Committee of Soviet Scientists for Peace Against Nuclear Threat, which is chaired by Academician E. M. Velikhov, and provided them with a draft paper on the nuclear winter issue.

Professor Kapitza also indicated that work was in progress, headed by G. S. Golitsyn and A. S. Ginzburg, at the Institute of Atmospheric Physics of the Academy of Sciences, and also at the Soviet Central Meteorological Administration, under Academician Israel.

It is probably worthy of note that Aleksandrov and Stenchikov performed the first nuclear winter related three dimensional general circulation calculations, on an extremely primitive computer, the BESM-6, at the Computer Center of the Academy of Sciences of the USSR. In fact, it appears that they have also performed the first three dimensional calculations that accounts for smoke motion in the atmosphere as well.

Professor Seymour Goodman, a distinguished scholar who studies Soviet science and technology, informs me that the BESM-6 computer was first announced in 1964, and about 200 were made between 1965-79. This computer is therefore extraordinarily primitive relative to those available for atmospheric calculations in the West, which may explain, at least in part, the lack of Soviet follow up calculations.

Aleksandrov and Stenchikov have, however, been active in collaborations with scientists in the West. I suspect that the lack of Soviet computational capabilities will severely hamper their activities in this area if they do not collaborate with scientists in the West.

On the other matters raised in question 4, I have no information on these questions that would not fall into the category of hear-say.

T. A. Postol QUESTION 5

5. Does a nuclear arsenal in excess of the climatic threshold enhance our national security?

Answer to 5

In my written testimony, I demonstrated that it might be possible to build a nuclear force of tens or hundreds of thousands of low-yield earth-penetrating warheads that if used to destroy Soviet society, would probably not bring about a climatic catastrophe. I was careful to point out, however, that such a force would not solve any of the security problems that confront us today. I believe similar reasoning, which follows from the view that the nuclear winter problem is only one element of a far larger set of problems, applies here as well.

A nuclear force well in excess of the climatic threshold might be invaluable as a threat to Soviet peripheral attack forces in Europe, military installations and staging areas that could support large conventional military incursions into Europe, and the like. If the nuclear force was not used against targets with high fuel loadings like cities, very many weapons in excess of the climatic threshold could be used.

Whether or not a credible threat that we might use such forces in response to Soviet aggression enhances deterrence or not, is for me, an imponderable question. However, if such a force did deter Soviet aggression, because it provided U.S. decision-makers with credible options against Soviet actions, such a force would obviously enhance our security. Hence, if a climatic threshold in fact exists, it is quite conceivable that a force that is greatly in excess of it, could considerably enhance our security.

6. What is your opinion on the idea of a treaty to ban the targeting of cities or installations co-located with cities?

Answer to 6

As I mentioned in my response to question 3, in my view, our nuclear policy should be clear, structured and coherent. If such a policy could be implemented, it would provide guidance for both military planning and diplomatic activities, which rather than being competitive, should instead be closely coordinated and mutually supportive activities.

Using this line of argument, diplomatic accords that do not have an identifiable (not to be mixed up with quantifiable) role to play in our national security planning, can at best produce nothing of value, and at worst, can introduce artificial constraints in our national security planning that make it more difficult for us to meet our overall planning objectives. Thus, the test of the value of a treaty would be the accomplishment of some identifiable objective that is compatible with an overall security strategy; when and if, of course, we ever develop such a stratey.

In the case of a ban on targeting of cities, I am unable to identify any such concrete security objective. There would be no way to guarantee that a decision to target cities could not be implemented on very short notice, even if all pre-planned targets in fact avoided cities. Since the threat of targeting cities would always be the last resort threat of both super-powers, not to mention the non-super-power nuclear weapon states, it is difficult for me to see how anything meaningful, political or military, could be accomplished by such a treaty.

7. Have officials in the U.S. Government been briefed on the nuclear winter issue by members of the scientific community? At what levels and by whom?

Answer to 7

The Chief of Naval Operations, the Vice Chief of Naval Operations, the Deputy Chief of Naval Operations for Plans, Policy and Operations, and the Director of the Navy's Strategic and Theater Nuclear Warfare Division have all been provided detailed scientific and technical summaries on the nuclear winter issue.

In fact, the Director of the Strategic and Theater Nuclear Warfare Division (Commodore R. F. Bacon) was sufficiently concerned about the preliminary scientific findings on the nuclear winter issue, that he wrote a letter to the Chairman of the Military Liaison Committee to DoE (The Honorable Dr. Richard Wagner) about the need for more DoD effort on this subject. This letter was written in July 1983, many months before the nuclear winter issue was brought to the attention of the public.

The Natural Resources Defense Council Nuclear Winter Project, has kindly provided me with a considerable amount of internal Navy materials, obtained through the Freedom of Information Act, that address various aspects of this issue.

Since much of this material could be of interest to the members of the Committee, they have provided copies of the Navy materials for the hearing records. These materials are attached to my testimony.

Although I know from my activities in the Pentagon that other high-level Government officials have given this issue considerable attention, I have no knowlede of who briefed them on this issue, nor do I know what they were told.

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

DEPARTMENT OF THE NAVY
OFFICE OF THE CHIEF OF NAVAL OPERATIONS
WASHINGTON, DC 20350

IN REPLY REFER TO
14 March 1984

Ms. Estelle H. Rogers
Natural Resources Defense Council, Inc.
1725 l Street, N.W.
Suite 600
Washington, DC 20006

Dear Ms. Rogers:

This is in reply to your Freedom of Information Act request of February 29, 1984, in which you seek any materials prepared by or for the Office of the Chief of Naval Operations concerning: (1) the scientific findings on the long-term environmental effects of nuclear war or (2) the policy implications of those findings. Your request has been carefully considered under the applicable provisions of the Freedom of Information Act, as amended (5 USC 552), and the implementing naval directive, Secretary of the Navy Instruction 5720.42C, Subj: Department of the Navy Freedom of Information Act Program.

Three documents related to your request have been located. Two are releasable and are enclosed. Upon review of the third document, it has been determined that substantial portions are properly classified in the interest of the national defense under the criteria defined in Department of the Navy Information Security Program Regulation (OPNAVINST 5510.1F), which implements Executive Order No. 12356. The cited regulation authorizes the classification of information pertaining to military plans and as such precludes its release.

Accordingly, it has been determined that the above-noted portions of the requested records are exempt from disclosure under title 5, section 552(b)(1), United States Code. It is further determined that a governmental interest exists for preserving the secrecy of these exempt matters, because of the need to protect military planning. Consequently, to the extent that one of the requested documents contains information which cannot be released, your request must be denied.

Although one of the requested documents cannot be released in its entirety, several meaningful portions of it are releasable. I have therefore directed that you be provided with a copy of those portions, and it is enclosed. Since they fall below the automatic fee waiver threshhold, fees in connection with your request have been waived.

Because your request has been partially denied, you are advised that it is your right under the cited statute and title 32, section 701.9, Code of Federal Regulations, to appeal this determination in writing to the designee of the Secretary of the Navy. Such an appeal, if made, should be addressed to:

Judge Advocate General
Navy Department
200 Stoval Street
Alexandria, VA 22332

The appeal must be received in that office 45 days from the date of this letter in order to be considered, and the enclosed copy of this letter should be attached. It is recommended that the letter of appeal and the envelope both bear the notation, "Freedom of Information Act Appeal."

The official responsible for the partial denial of your request is:

Commodore Roger F. Bacon, USN
Director,
Strategic and Theater Nuclear Warfare Division
Office of the Chief of Naval Operations

If you have any questions concerning the foregoing, Captain L. F. Brooks, USN, telephone (202) 695-6578, is familiar with your request and will be glad to help you.

Sincerely,

R. F. BACON
Commodore, U.S. Navy
Director,
Strategic and Theater
Nuclear Warfare Division

Encl:
DCNO (Plans, Policy and Operations) Memo 7 November 1983
DCNO (Plans, Policy and Operations) Memo 19 November 1983
Deputy Director, Strategic and Theater Nuclear Warfare Division
Memo 7 November 1983 (Sanitized)

DEPARTMENT OF THE NAVY
OFFICE OF THE CHIEF OF NAVAL OPERATIONS
WASHINGTON, DC 20350

IN REPLY REFER TO
65B Memo 393/A112102-07
07 NOV 1983

MEMORANDUM FOR THE CHIEF OF NAVAL OPERATIONS

Subj: "The World After Nuclear War"

Encl: (1) Technical Summary
(2) Conference Synopsis

1. This memorandum summarizes the results of "The World After Nuclear War" Conference held in Washington on 31 October and 1 November. The conference presented evidence that a large scale nuclear exchange (roughly the size of a SIOP/RISOP exchange) could lead to an environmental catastrophe that could cause the extinction of man. The conclusions, which are significantly more severe than previously believed, are probably generally valid and will be widely accepted in the scientific community. Soviet interest in the results, and in manipulating those results to support Soviet arms control positions, was evident. Conference results may raise both long term policy issues and short term public relations problems.

2. The technical results of the conference show that a nuclear exchange of 5000-10,000 megatons could lead to the following:

a. Radiation levels in the Northern Hemisphere ten times higher than previously expected.

b. A so-called "nuclear winter" of Arctic conditions throughout the Northern Hemisphere lasting for several months and caused by the blocking of sunlight from dense smoke and dust injected into the upper atmosphere from fires at target areas.

c. Flooding on a continental scale during the "nuclear winter" resulting from heating of the upper atmosphere (above the smoke and dust) and the subsequent melting of ice and snow on the mountain tops.

d. A period of temperatures 30-40° above normal once the dust settles following the "nuclear winter."

e. As a result of all the foregoing, an ecological disaster of unprecedented proportion, possibly extending to the physical extinction of man.

The conference results have been extensively reviewed by the scientific community. In addition, VADM William Moran (former OP-098) advises us that they are generally similar to the anticipated results of a separate National Academy of Sciences study commissioned by Under Secretary of Defense DeLauer. Thus in broad terms the results are probably correct and will certainly be so viewed by the scientific community. Additional details are at enclosure (1).

Subj: "The World After Nuclear War"

3. The most scientifically advanced calculations presented at the conference were reported, unexpectedly, by an atmospheric physics group of the Academy of Sciences of the Soviet Union. Although the Soviets attempted to present their findings in a low key manner, they were clearly trying to take advantage of the conference for political purposes. Political overtones were most evident in the live satellite link between a panel of Soviet academy members in Moscow and U.S. conference participants in Washington. A more detailed summary of the conference is at enclosure (2).

4. In the long term, the conference results deserve serious study to see what, if any, changes in U.S. targeting policy are required. In the short term, however, the conference implications are primarily political. I anticipate that the Soviets will make extensive use of these results, especially in Europe, to demonstrate the dangers of the arms race (by which they mean PERSHING II/GLCM deployment). The United States can, however, point to substantial work in this area by the Departments of Defense and Energy and is in a good position to counter Soviet propaganda.

5. The Office of the Secretary of Defense has the lead on this matter. We will keep you informed.

Very Respy

JA Lyons

J. A. LYONS, JR.
VICE ADMIRAL, U.S. NAVY
DEPUTY CHIEF OF NAVAL OPERATIONS
(PLANS, POLICY AND OPERATIONS)

Copy to:
VCNO
OP-098
OP-981
OP-65

TECHNICAL SUMMARY

Conference on the Effects of Nuclear War on the Atmosphere (U)

1. This enclosure reports technical and scientific observations concerning the findings announced at the conference The World After Nuclear War.

2. The scientific findings presented at the conference indicate that a nuclear exchange of 5000 to 10000 megatons could result in the extinction of man. This previously unforeseen projection has been reviewed by more than 100 physicists, atmospheric scientists, and biologists from the U.S., the U.S.S.R., and other countries. The result has not been challenged by any of the scientists that participated in the review.

3. These strikingly new estimates of the impact of nuclear war on human life follow from new physical calculations of atmospheric effects that would accompany a nuclear exchange. The physical results are briefly summarized below:

a. Large fires initiated in target areas will inject dense smoke into the atmosphere, shielding the surface of the earth at mid-northern latitudes from sunlight.

b. The decrease in the amount of light reaching the surface of the earth will cause the temperature to drop, within a few days of the exchange, some 50 to 70 degrees Fahrenheit at mid-northern latitudes.

c. The slow settling of radioactive dust dispersed in the lower atmosphere will cause average radiation levels across the entire northern hemisphere to be ten times higher than previously expected.

d. Since sunlight drives the natural circulation of the atmosphere, and the atmosphere will be optically modified, the average global motion of the atmosphere will change. This will result in a massive, and previously unpredicted, impact on the southern hemisphere.

e. Sunlight depositing energy in the upper atmosphere will result in a relative warming of the upper atmosphere, posssibly resulting in the melting of mountain snow and glaciers. Floods of continental scale could result from such melting.

f. At the end of the "nuclear winter" (which could occur about one year after the exchange), a possible "nuclear summer" will follow. The nuclear summer will most likely be confined to the northern hemisphere, characterized by temperatures 35 to 45 degrees Fahrenheit above those normally occurring. The nuclear summer occurs because the upper atmosphere is initially heated by sunlight while soot and dust are present. As the soot and dust settle out, the warmer upper atmosphere then contributes to heating at the earth's surface.

g. During this period, the surface of the earth would also be unmasked to ultraviolet beta (UV-B) radiation, which would reach the surface of the earth because the normally present stratospheric ozone "shield" had been depleted. Intensities of UV-B could be sufficiently strong to destroy or severely injure many types of plants. Certain mammals could suffer blindness, and humans could suffer severe sunburns after skin exposure for periods of fractions of an hour.

4. The physical effects outlined above will have immediate and irreversible consquences for all ecological systems on the planet. However, due to the relative immaturity in our understanding of ecosystems, the scale and nature of many significant effects have not yet been quantified. In spite of these uncertainties, the community of biologists reviewing the physical results were unanimous in the following conclusions:

a. The combined effects of reduced sunlight, extreme cold, and radiation will result in a biological disaster of unprecedented proportions since the possible impact of a giant meteorite during the Cretacious-Tertiary period some 65 million years ago. This event is widely believed to have caused the massive extinctions observed by paleontologists during that period.

b. The sudden drop in light fluence and temperature at the earth's surface will result in the large scale permanent destruction of many species of vegetation, the inhibition of the photosynthetic processes in any surviving vegetation on the planet, and the complete destruction of northern hemispheric forests and croplands.

c. The reduced level of sunlight entering the oceans will result in the death of most of the phytoplankton (small one celled plants) in the oceans of the Northern Hemisphere. Since the phytoplankton are at the base of the food chain upon which all ocean life depends, massive disruptions and possible extinctions of ocean animals and plants would be a certainty.

d. During the period of continental thaw, the melting of ice and glaciers from mountain tops will result in a massive erosive runoff from the continents. This will increase turbidity in the oceans, further reducing the rate of recovery of phytoplankton. It will also result in the loss of enormous amounts of irreplaceable topsoil. This latter phenomenon will further inhibit agricultural recovery of continental areas.

e. The biological implications of the period of heating, following the period of cooling, was not evaluated by the biologists since the period of heating was reported for the first time at the conference by the Soviets.

f. The consensus of the biologists reviewing the impact of environmental effects on the ecosystem was that the scale and diversity of ecological upheaval would be so extensive that the extinction of man could not be ruled out.

5. The conference findings concerning the "nuclear winter" and its catastrophic effects are broadly similar to the findings of a separate Lawrence Livermore National Laboratory study and the anticipated findings of a forthcoming study undertaken by the National Academy of Sciences at the request of USDRE. These results thus almost certainly will be widely accepted in the scientific community.

November 3, 1983

Summary of Activities at The World After Nuclear War Conference

The conference began on the morning of Monday, October 31, with a press conference. The press conference was chaired by Dr. George Woodwell, Director of the Ecosystems Laboratory in Woods Hole, Massachusetts, who repeatedly stressed that only scientific questions would be addressed by conference participants.

The main body of scientific findings was presented by Dr. Carl Sagan and Dr. Paul Ehrlich. Dr. Sagan is the Director of the Laboratory for Planetary Physics and David Duncan Professor of Astronomy at Cornell University. Dr. Ehrlich is the Bing Professor of Population Studies at Stanford University.

Dr. Sagan presented a careful tutorial on the atmospheric effects to be discussed at the conference. The discussion was largely repetitive. The press kept asking questions which indicated a lack of understanding of the findings and Sagan patiently went over the same ground clarifying points, correcting misstatements of fact and refusing to answer questions related to policy.

Dr. Ehrlich then presented the biological findings, which he emphasized followed from an assessment of the impact of the estimated atmospheric effects calculations. He also emphasized that catastrophic biological disruption would accompany environments considerably less severe than those discussed by Sagan. In contrast to Sagan, Ehrlich had almost nothing quantitative to say. Therefore, from a scientific point of view, it was impossible to understand what he meant when he repeatedly emphasized catastrophic biological consequences in less severe environments.

In the afternoon, Dr. Donald Kennedy, President of Stanford University, addressed the conference on "Decision Making in Uncertainty." Dr. Kennedy was Commissioner of the Food and Drug Administration in 1977 and, prior to that, Chairman of the Program in Human Biology at Stanford University. He discussed the problems of trying to make informed decisions in the absence of adequate information. He related the discussion to the evolution of testing and research in toxicology, and its relationship to public policy. He then related the importance of the findings to be presented in the conference to the need for information in support of decision making.

Enclosure (2)

Dr. Sagan then presented an hour long discussion of the atmospheric effects findings to the conference. His talk was a more detailed recapitulation and explanation of the material presented earlier to the press. He concluded his talk with a short, extremely slick, and professional animated color film summarizing the material presented in his talk.

Dr. Ehrlich then presented his discussion of the biological effects, also covering the same ground as was covered in the earlier press conference. Unlike Sagan's talk, which was accompanied by slides and additional detail, Ehrlich's comments were merely the same qualitative rehash of his press conference remarks

On the morning of the second day there was a panel presentation which, unexpectedly, contained the most significant new scientific work at the conference. This work was presented in a 10 minute talk by Dr. V. V. Aleksandrov of the U.S.S.R Academy of Sciences. A small number of preprints describing the Soviet work were made available.

Dr. Aleksandrov described an extremely advanced and ambitious three dimensional hydrodynamical computer calculation, modelling the average motion of the atmosphere after a nuclear war. The model is capable of describing large-scale atmospheric motions, including modifications of that motion from land masses, oceans, evaporation, and the like. These calculations were by far the most advanced presented at the conference and represent a quantum jump in detail over the work of Sagan and his colleagues.

Later in the day the Soviets tried to exploit this contribution, to interject political overtones into the scientific discussion.

There was also a presentation by Dr. Stephen Schneider, Deputy Director of the Advance Study Program of the National Center for Atmospheric Research at Boulder, Colorado. Dr. Schneider indicated that similar work at the National Center was in qualitative agreement with the findings reported by the Soviets. However, he did not present any detailed results.

Later in the morning a similar panel of biologists presented their findings. The only discussion that contained any quantitative results was that presented by Dr. Joseph Berry of the Department of Plant Biology, the Carnegie Institution of Washington, Stanford, California. Dr. Berry presented data that indicated that even if a catastrophic drop in the ambient temperature did not accompany the drop in light levels, plant life would suffer a major biological catastrophe due to the loss of photosythetic energy.

In the afternoon of the second day, the politically most interesting conference activity occurred. This was a live satellite link with members of the Soviet Academy of Sciences. This satellite link-up was not in any of the formal schedule announcements associated with the conference, and had the appearance of a late development in the conference planning. The announcement of the satellite link was folded into the Conference Program as an add-on. Although the American panelists were listed by name, the Moscow panelists names were listed as "to be announced".

During the course of the panel discussion, one of the Soviets, Nikita Moiseev, Director of the Computer Center of the Academy of Sciences of the U.S.S.R., was allowed to address the Moscow panelists from the Washiington conference. He made a big point of emphasizing the significance of the findings presented at the conference and the role of the Soviet scientific establishment in the conference. He then went on to emphasize that three important insights came out of the work presented at the conference. These points were:

1. The climatic consequences of nuclear war would be catastrophic.

2. The biological consequences would also be catastrophic

3. The need for arms control was greater than ever.

This last point was stated in an extremely elaborate and circumlocutious manner, indicating some attempt, albeit somewhat clumsy, to veil the political nature of his supposedly scientific observations.

Also of interest was that the Soviet panelists participating from Moscow had nothing of scientific substance to contribute to the discussion. The panel had the appearance of a clumsily orchestrated wooden restatement of material that was already evident to any informed scientific observer at the conference.

Conclusions

The findings presented in the conference, The World After Nuclear War, must be viewed as a serious, credible, result of scientific enquiry into possible consequences of nuclear war. However, a considerable amount of serious scientific work will be required before a better understanding of these consequences emerge.

It appears that this problem has gotten high level attention in the Soviet Union. Considerable scientific and computational resources have been devoted to this problem by Soviet academicians and there is clearly an interest in capitalizing on these efforts politically.

65B Memo C396
7 Nov 83

~~CONFIDENTIAL~~

DECLASSIFIED

From: OP-65B
To: OP-654

Subj: New In-house Study

1. The recent conference "The World After the Nuclear War" suggests that a SIOP scale exchange could result in the extinction of man. Broadly similar conclusions were drawn by a Livermore study and will probably be drawn by a forthcoming National Academy of Sciences effort. While I personally have always questioned whether "post-SIOP" has any real meaning, these new findings are still worth paying attention to. Unfortunately, as far as I can tell, there is little likelyhood of a serious examination of the broad policy implications being done by anyone knowledgable in OSD/JCS. understands the issues but almost certainly lacks time/resources to look at them in depth. Therefore I propose that we take a look.

NAMES DELETED TO PROTECT PRIVACY "EXEMPTION 6"

2. I suggest that and one 654C analyst who understands the SIOP do a paper on the policy implications of these findings. The object would be to see what changes in targeting policy or declaratory policy these results might suggest. Since it is a policy look, not a technical look, we should assume that the broad conclusions presented are correct.

3. Some of the issues that suggest themselves for consideration are:

a. Is the attack that Sagan assumed representative of the actual SIOP? As I understand the results, smoke and soot from burning cities are the trigger mechanism for the climatic changes. But I believe Sagan assumed 20% of an attack was directed at cities.[ ]

b. How close in size are[ ]to the threshold hundred megatons that Sagan suggests might trigger climatic changes. There is enough problem with[ ]now; if a particular[ ]approach would lead to the de facto destruction of [ ]even if[ ]did not shoot back that would be a fact worth knowing.

CLASSIFIED MATERIAL DELETED. "EXEMPTION 1"

c. Are counterforce attacks by either side possible without climatic impact? It may be that a first strike is, quite literally, suicidal, not because the adversary will retaliate but because the very strike on the opponent destroys the attacking nation as well through the mechanisms of climate.

d. What does all this say for the desirability (not for the feasibility) of strategic defense. Even if defense cannot be made leak-proof, can it somehow hold an attack below the level at which climatic changes are triggered?

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DECLASSIFY: OADR

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DECLASSIFIED

Subj: New In-house Study

4. Other questions will doubtless suggest themselves as we go along. I would think you would want to bounce ideas off not only people down there but 65D and 651.

5. Think this over and let me know your thoughts.

L. F. BROOKS
Captain, U.S. Navy
Deputy Director,
Strategic and Theater
Nuclear Warfare Division

Copy to:
OP-65
OP-65D
OP-651

DEPARTMENT OF THE NAVY
OFFICE OF THE CHIEF OF NAVAL OPERATIONS
WASHINGTON, DC 20350

IN REPLY REFER TO
65B Memo 403
19 NOV 1983

MEMORANDUM FOR THE CHIEF OF NAVAL OPERATIONS

Subj: "The World After Nuclear War"

Encl: (1) OP-06 memo, same subject of 7 Nov 83

1. In enclosure (1) I summarized the results of the recent conference on "The World After Nuclear War." I stated that, while I expected the Soviets to make extensive use of the conference results in Europe, the United States was in a good position to counter Soviet propaganda. In commenting on enclosure (1) you asked how such propaganda could be countered.

2. In my judgement the Soviets will use the following themes;

a. The fact that the conference was unofficial and the results were surprising shows that the United States has not studied the problems of the nuclear age seriously, leading to a dangerous and cavalier attitude towards nuclear war. Counter arguments:

- Over a year ago the Department of Defense commissioned a National Academy of Sciences Study on the environmental effects of nuclear war.
- The Department of Energy, through Lawrence Livermore National Laboratory, has conducted similar examinations.
- The Defense Nuclear Agency conducts an ongoing examination of these subjects.
- The Department of Defense is assessing the policy implications of the new knowledge these examinations have revealed.
- Thus the United States is taking the scientific results seriously.

b. Conference results show nuclear war would be the effective end of civilization. Thus it must be prevented at all cost. Counter arguments:

- The United States agrees. President Reagan recently told the United Nations General Assembly that "A nuclear war cannot be won and must not be fought."
- The issue is how best to prevent such a disaster.
- The United States preference is for significant arms reductions. However the Soviets have taken advantage of U.S. restraint leaving the U.S. no alternative except the President's Strategic Modernization Program.

Subj: "The World After Nuclear War"

c. The horror of nuclear war revealed by the conference make Arms Control vital for the survival of mankind. Counter arguments:

- The United States agrees. It is the United States which has proposed deep reductions in nuclear arms, proposals which the Soviet Union has yet to discuss seriously.
- Equitable and verifiable arms reduction remain US goals. Failure to reach agreement is due to Soviet unwillingness to negotiate seriously.

3. In summary, we have done enough scientific examination of our own to counter charges of failing to take the subject seriously. The theme that nuclear war is so destructive it must be prevented is not new; the conference report simply adds to an existing, widely held belief that nuclear war must be avoided at all cost. Thus, while the Soviets will try to use these results to their advantage, I do not believe that the disclosures of environmental impact of large scale nuclear weapons use will significantly advance the Soviet cause.

Very Respy
JA Lyons Jr.

J. A. LYONS, JR.
VICE ADMIRAL, U.S. NAVY
DEPUTY CHIEF OF NAVAL OPERATIONS
(PLANS, POLICY AND OPERATIONS)

Copy to:
VCNO

See reverse for instructions—Complete necessary blocks, only

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ATTACHED OUTGOING DOCUMENT	TYPE	ADDRESSEE(S)	SERIAL
	MEMO	CNO	403

SUBJECT: "The World After Nuclear War"

BACKGROUND/BRIEFING (If required, list references and enclosures immediately below, in naval letter format. It is not necessary to list references and enclosures to the basic incoming and outgoing documents. Duplication of information contained in the attached incoming or outgoing document, or that inserted elsewhere on this sheet, should be avoided wherever practicable.)

- OP-06 memo of 7 November informed CNO of the Carl Sagan conference "The World After Nuclear War."

  -- Suggested Soviets would use for propaganda
  -- But U.S. was in good position to counter

- CNO asked "how."

- This memo responds to CNO question.

- Recommend OP-06 sign.

☐ CONTINUED ON PAGE 2

ROUTE TO
INSERT ORDER NO. OR "X" MARK THROUGH WHEN RELEASED*
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L.F.BROOKS,CAPT USN	OP-65B 56578	14 Nov 83

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DEPARTMENT OF THE NAVY
OFFICE OF THE CHIEF OF NAVAL OPERATIONS
WASHINGTON, DC 20350

IN REPLY REFER TO
29 May 1984

Ms. Estelle H. Rogers
Natural Resources Defense Council, Inc.
1725 I Street, N.W.
Suite 600
Washington, DC 20006

Dear Ms. Rogers:

On March 14, 1984 I replied to your Freedom of Information Act request of February 29, 1984, in which you sought any materials prepared by or for the Office of the Chief of Naval Operations concerning: (1) the scientific findings on the long-term environmental effects of nuclear war or (2) the policy implications of those findings. Your request was carefully considered under the applicable provisions of the Freedom of Information Act, as amended (5 USC 552), and the implementing naval directive, Secretary of the Navy Instruction 5720.42C, Subj: Department of the Navy Freedom of Information Act Program. Three documents related to your request, one of which was sanitized, were forwarded with that letter. Upon additional search two earlier documents pertaining to your request have been located. Upon review it has been determined that substantial portions are properly classified in the interest of the national defense under the criteria defined in Department of the Navy Information Security Program Regulation (OPNAVINST 5510.1F), which implements Executive Order No. 12356. The cited regulation authorizes the classification of information pertaining to military plans and as such precludes its release.

Accordingly, it has been determined that the above-noted portions of the requested records are exempt from disclosure under title 5, section 552(b)(1), United States Code. It is further determined that a governmental interest exists for preserving the secrecy of these exempt matters, because of the need to protect military planning. Consequently, to the extent that the requested documents contain information which cannot be released, your request must be denied.

Although the requested documents cannot be released in their entirety, several meaningful portions are releasable. I have therefore directed that you be provided with copies of those portions, and they are enclosed. Since they fall below the automatic fee waiver threshold, fees in connection with your request have been waived.

Because your request has been partially denied, you are advised that it is your right under the cited statute and title 32, section 701.9, Code of Federal Regulations, to appeal this determination in writing to the designee of the Secretary of the Navy. Such an appeal, if made, should be addressed to:

Judge Advocate General
Navy Department
200 Stoval Street
Alexandria, VA 22332

The appeal must be received in that office 45 days from the date of this letter in order to be considered, and the enclosed copy of this letter should be attached. It is recommended that the letter of appeal and the envelope both bear the notation, "Freedom of Information Act Appeal."

The official responsible for the partial denial of your request is:

Commodore Roger F. Bacon, USN
Director,
Strategic and Theater Nuclear Warfare Division
Office of the Chief of Naval Operations

If you have any questions concerning the foregoing, Captain L. F. Brooks, USN, telephone (202) 695-6578, is familiar with your request and will be glad to help you.

Sincerely,

R. F. BACON
Commodore, U.S. Navy
Director,
Strategic and Theater
Nuclear Warfare Division

Encl:
Director, Strategic and Theater Nuclear Warfare Division
Memo 26 Jul 1983 (Sanitized)
Director, Strategic and Theater Nuclear Warfare Division
Memo 7 Oct 1983 (Sanitized)

DEPARTMENT OF THE NAVY
OFFICE OF THE CHIEF OF NAVAL OPERATIONS
WASHINGTON, DC 20350

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IN REPLY REFER TO
65B Memo S367
7 October 1983

~~SECRET - CONFIDENTIAL upon removal of enclosure~~

MEMORANDUM FOR THE CHIEF OF NAVAL OPERATIONS

Via: Deputy Chief of Naval Operations (Plans Policy and Operations)

Subj: Environmental Effects of Nuclear War (U)

Encl: (1) Memo to Chairman MLC

1.(U)~~(S)~~ In my capacity as Navy member of the Military Liaison committee (MLC) I suggested to Dr. Rich Wagner, MLC Chairman, that he direct an examination of the possible environmental effects of a large scale nuclear exchange. This information is potentially important for military planning. Investigation of these effects is in progress outside of the federal government and might be a source of embarrassment if the Department of Defense has not examined the questions.

2. (U) The American Academy of Sciences, directed by Dr. George Carrier, is conducting this evaluation at the request of Dr. DeLauer. I understand that you have been briefed on this effort by [ ]and wanted you to be aware of my similar steps.

3. (U) A copy of my memorandum is attached for your information.

VERY RESPECTFULLY

R F Bacon

R. F. BACON
Commodore, U.S. Navy
Director,
Strategic and Theater
Nuclear Warfare Division

Copy to:
VCNO
OP-981

INDIVIDUAL
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DEPARTMENT OF THE NAVY
OFFICE OF THE CHIEF OF NAVAL OPERATIONS
WASHINGTON, DC 20350

DECLASSIFIED

IN REPLY REFER TO
OP-654E4/TP:sl
Ser 654/S430743
JUL 26 1983

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MEMORANDUM FOR THE CHAIRMAN, MILITARY LIAISON COMMITTEE

Subj: Military Planning for Operations in Possible Nuclear Environments

(U)~~(S)~~ A review of recent scientific work on the environmental impact of large scale nuclear exchange indicates important implications for military planning.

(U) In a recent article by Paul Crutzen and John Birks[1] of the Max Planck Institute in Mainz Germany and the Institute for Research in Environmental Sciences at the University of Colorado, it was shown that the effects of fires immediately following a nuclear war could result in the injection of large quantities of optically-absorbing particulate matter into the atmosphere. This phenomenon could potentially reduce the amount of sunlight reaching the earth's surface by as much as two orders of magnitude, resulting in night-like conditions across the entire northern hemisphere.

(U) Additional scientific work has been done by groups based at Harvard, RDA and Cornell indicating that a major impact on the atmospheric chemistry and terrestrial climate cannot be ruled out. These results are in contradiction to the findings of the 1975 National Academy of Sciences (NAS) study and are currently under review in a second NAS study.

(U) The findings of the RDA-Cornell group (soon to be reported in the journal SCIENCE) indicate that major atmospheric perturbations are possible at fairly low levels of exchange (hundreds of megatons). If such a change is correctly predicted by this work, the atmospheric change would be largely due to the sudden input of sunlight-absorbing smoke from mass fires.

(U) My technical advisor recently attended a scientific meeting at the DNA at which the above mentioned work was reviewed by him, a member of IDA, DNA contractors and members of the Harvard, RDA, and Cornell groups. He reports to me that the consensus of the meeting was that while the reported work raises many scientific questions, it is a scientifically sound first cut at a complex problem and is worthy of serious additional scientific research.

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OP-654E4/TP:sl
Ser 654/S430743
JUL 26 1983

(S) A question raised by this work is the impact of changes in the atmosphere's absorption, transmittance and reflectivity. The combined effects of smoke and atmospheric chemistry could have a detrimental effect on [redacted] assets.

(S) Of particular concern are indications of significant atmospheric perturbations at relatively low levels of conflict. In these circumstances, the infrared albedo could change [redacted] sufficiently to seriously degrade the capability of [redacted] making attack assessment considerably more difficult in [redacted] nuclear conflicts. This, in turn, could seriously impact capabilities critical for [redacted]

(S) Other possible impacts of such environments are [redacted] In addition, EHF satellite links, which can be sensitive to particle loading in the air, may suffer performance degradation at a time when the [redacted]

(U) For the above stated reasons, I recommend the Military Liaison Committee request the Defense Nuclear Agency to initiate a program oriented toward better defining the Post-SIOP environment and its impact on critical military systems. It may also be prudent to task them with identifying and evaluating possible impacts on critical military systems other than those mentioned above.

R F Bacon
R. F. BACON
Commodore, U. S. Navy
Director,
Strategic and Theater Nuclear
Warfare Division

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[1] Crutzen, P. J., and J. W. Birks, "The Atmosphere After Nuclear War: Twilight at Noon," Ambio, 11, 114-125 (1982)

Turco, R. P., Toon, O. B., Ackerman, T., Pollack, J. B., and Sagan, C., "Long-Term Atmospheric and Climatic Consequences of a Nuclear Exchange," Draft, March 1983

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DECLASSIFIED

T. A. Postol COMMENT 1

Recommendation to Congress on How to Evaluate The President's STRATEGIC DEFENSE INITIATIVE

(Page 1 of 4 Pages)

Since the question of whether or not the United States should develop and/or deploy a "Star Wars" defense has been raised in this hearing by both questions posed to me, and comments made by Dr. Teller, I would like to suggest a policy structure which each member of Congress can use as a basis for evaluating various "Star Wars" related claims and proposals.

I would recommend that the Congress support no decision to deploy or develop "Star Wars" defenses, or any other types of defenses against nuclear weapons, without first having the answers to the following five technical questions:

1. Is the defense technically feasible?
2. Does its application provide useful levels of protection?
3. Can it be countered?
4. Will the counters be of such a nature that the overall security posture of the country will be degraded?
5. Do the technical characteristics of the defense create new security issues?

For example, although the Soviets may have bought some very modest level of local protection with the Moscow ABM system, their defense stimulated a vast increase in the number of U.S. warheads as a counter (the U.S. MIRVed in response to the Moscow defense). The counter stimulated by the Moscow defense therefore degraded the overall security circumstance of the Soviet Union. Thus, had Soviet leadership obtained an accurate answer to question four, they might not have chosen to deploy the GALOSH system

Consider another example. If the Soviets and the U.S. chose to build very capable defenses that only worked at low altitudes in the atmosphere, the defenses might unambiguously serve only the purpose of defense. If both sides instead built space based defenses, capable of engaging boosters at very long range, then each defense might be able to attack the other, or each defense might be used to attack the other's early warning and communications satellites. Thus, an accurate answer to question five would reveal to the Congress that the characteristics of this second type of defense would result in the introduction of a whole new set of national security problems.

Thus, the failure to obtain accurate answers to the above five technical questions could result in a costly trade of one set of national security problems for another; or worse yet, it could result in the substitution of a far more serious set of national security problems for those that certain proponents of defense have argued would be solved.

It is extremely important for members of Congress to understand that the levels of performance required of a defense will vary drastically with its mission. If the objective of the defense is to guarantee that some fraction of otherwise vulnerable nuclear forces can survive attack, guaranteeing an ability to retaliate, then much less than "perfect" defense will be adequate. If the mission of the defense is instead to guarantee the survival of a city, then the defense must be able to handle the severest and most determined of attacks with perfection. Hence, a defense that is most robust in the role of defense of nuclear forces, could be completely inadequate for defense of cities.

Although there are many roles that have been argued for a defense, these two most basic ones, defense of population, and/or defense of nuclear forces are of greatest significance. If such defenses were successfully implemented by all nuclear-armed adversaries, they would drastically impact the deterrent relationship between them.

Just to illustrate how fundamental these defensive roles can be, consider the possibility that all parties successfully implement some form of defense. If all parties successfully implemented population defenses, it would eliminate the mutual hostage relationship, an elemental characteristic of deterrence. If all parties successfully implemented a defense of otherwise vulnerable nuclear forces, it would remove any hope, and therefore any incentive, that either adversary could preemptively destroy the retaliatory capability of the other. Thus, in both possible applications, the successful implementation of complex and robust defenses by all nuclear-armed adversaries would either enhance deterrence or eliminate the need for it.

However, if all sides depended on such defenses, powerful incentives would exist to modify or build additional forces to overwhelm them. In addition, many military planning complexities, and the ambiguities that accompany such planning, would add further complexity to an already complex structure of interacting military and political incentives.

For example, a situation could arise where two adversaries choose to defend vulnerable nuclear forces. One builds a very capable defense for only part of its force, the other builds a modest defense for all of its force.

In this postulated circumstance, the adversary with the partially defended nuclear force might then have a strong incentive to use its undefended force to destroy as much of its enemy's defended force as the offense-defense interaction would allow. Then if its enemy responded by retaliating, the remainder of its nuclear force might then be defendable, resulting in a post-exchange superiority of the attacker. If the attacker's defenses were sufficiently flexible, they might even be used to try and limit damage to cities as well as retaliatory forces.

While it by no means follows that such a situation would evolve from deterrent postures based on defended nuclear forces, complications would abound, and technical intricacies of force disposition and system capabilities could potentially be of considerable military significance. For these reasons, it cannot be accepted at face value that the succcessful implementation of defenses for nuclear forces or populations results in enhanced deterrence.

Further complicating the problem is that each adversary might simply build more warheads to attack each others cities and nuclear forces. Warheads could be reallocated so as to stress or destroy certain critical components of defenses. Tactics could be modified, sensors could be attacked, sabotage might be attempted, and devices to confuse or exhaust the defense could be built. Neither side might have confidence that they could successfully retaliate if attacked, and neither side might have confidence that their defense was in fact working.

In reality, a defense deployed to defend nuclear forces would have a finite capability. Whether or not it is, by some measure, very capable or very limited, it would only be able to intercept a finite number of attacking warheads. If enough warheads arrived in a sufficiently short interval of time, it might be overwhelmed. In addition, even with very advanced and capable sensors, it might not be able to tell decoys from real warheads. Even a very robust and capable defense would have such limits, and the viability of the defense would depend on the scale, innovation, and determination of any enemy attack against it.

If instead the defense was deployed to protect cities, only the smallest amount of success would be required of the offense, and only perfect performance could be tolerated of the defense. Thus, any meaningful level of city defense would demand a most commanding superiority of defense over offense. While it is not provable that such a combination of unchallengable superiority and perfection in performance could never be achieved, it would be unprecedented in the history of human conflict.

I would now like to briefly expand on the issue of defense characteristics, raised by my proposed fifth question. As I have already noted, defenses of apparently equal capability, but different characteristics, could have a very different affect on the deterrent relationship between adversaries.

If, for example, two adversaries could build "perfect" defenses, utilizing some as yet unknown principle of physics to build a force field which no nuclear weapons could penetrate, then the mutual hostage relationship which is so elemental to deterrence would cease to exist. However, it would also cease to be important as a means of avoiding the catastrophe of a nuclear war.

But what if the defense was not a shield, but instead was a very powerful, very long range and irresistably potent beam of energy, capable of knocking anything out of the sky, anywhere around the earth. Could not two such enormously potent systems also attack each other?

If both adversaries possessed two such perfect defenses, then a clear and unambiguous advantage would accompany the adversary that struck first. First negating the enemy's defense, then threatening the enemy with a nuclear attack which could no longer be deterred by threats of retaliation.

Nowhere is this question of defense characteristics more worrisome than when the defenses are based in space. One can imagine large and capable battle stations, that if sufficiently capable to engage ballistic missiles, would surely be able to engage each other. In fact, if they could not, the defense would not be capable of its most important function, defending itself so that it can survive to defend its masters!

However, what if one adversary chose to defend itself with a space based system, while the other instead chose a ground based one. Since many (but by no means all) ground based defense concepts have the capability to attack incoming ballistic warheads while they are still in space (at altitudes of hundreds of miles), they might also be capable of attacking space based battle stations, which would likely be at no higher altitudes than incoming warheads, and move at no higher speeds. Since the ground based system would not have to be lifted into space, it could be hardened to a space based counterattack much more easily than the orbiting system. In this circumstance, the differing characteristics of the defenses would result in an unambiguous assymmetry, leaving one side exposed to the unanswerable threats of the other.

Thus, the consequences of defensive deployments abound with issues that could threaten to destabilize existing deterrent relationships between adversaries. For this reason, a decision to deploy defenses against nuclear weapons, without first answering the five basic technical questions posed above, would in my view be highly imprudent.

T. A. Postol **COMMENT 2**

Comment on Dr. Teller's
Statement to the Committee
on the Government's Secrecy Policies

I would like to respectfully take issue with some aspects of Dr. Teller's earlier statement in this hearing "(that) discussions on all aspects of war should be made public; (and) that the policy of secrecy should be drastically reduced....".

There are very few threats posed to our democratic institutions and the competitive health of our society more serious than those posed by Government activities that are protected through a policy of secrecy. Government secrecy creates opportunities for abuse of authority, inefficiency, limits the possibilities for constructive external review of matters that can be of vital interest to the national security, and creates a difficult to control and monitor security system that can be filled with abuses of authority, inefficiency, and opportunities for political and civil liberties abuses.

However, I must strongly disagree with Dr. Teller's suggestion that discussions "on all aspects of war should be made public". There are many military operations and activities that are of the greatest sensitivity. There is absolutely no doubt in my mind that public discussion of these operations and activities would cause extremely grave, direct and immediate harm to our national security. It is simply unthinkable to me that this kind of information could ever be made available to the general public.

I do agree with Dr. Teller's second point, that there should be a drastic reduction in the amount of information that is treated as classified. A great deal of general technical information, which is basically available to experts outside of the Government is unnecessarily and unwisely classified. A great deal of technical information that is supposed to be based on intelligence, is also, in my opinion overclassified or improperly classified.

This has three serious deleterious effects on our Government: Individuals within the system, even individuals who have clearances, can often not obtain needed data or information because of improper or overclassification; respect for classified information is eroded, resulting in security problems that can lead to the inadvertent release of sensitive information; and individuals external to the system are denied access to information that could contribute to vitally useful analysis and public debate on national security issues of great importance.

T. A. Postol COMMENT 3

Comment on the Scientic Contributions of the TTAPS Paper

Since it appears that Dr. Teller and Dr. Sagan have differences about the significance and value of the paper on the nuclear winter effect published by R. P. Turco, O. B. Toon, T. P. Ackerman, J. B. Pollack, and C. Sagan (TTAPS) in the December 1983 issue of SCIENCE, it may be useful if I too share my views on this work with the Committee.

When a physical phenomenon is not well understood, or it is not clear whether or not it is significant relative to other competing physical effects, it is common for initial scientific investigations to "scope the problem" with simple model calculations. Such calculations are often very useful as a means of determining whether or not a significant investment of additional effort is merited, and they can also be most valuable in providing guidance for more complex, time consuming, and costly follow-on calculations.

In my view, this was the purpose and intent of the model calculations presented in the TTAPS paper. The paper made, of necessity, many carefully caveated assumptions, as well as many carefully caveated speculations. I agree with both Dr. Teller and Dr. Sagan that different assumptions would result in different predicted results. This was unambiguously demonstrated in the TTAPS paper for a wide variety of differing assumptions.

The very ambitious scientific program being funded through the National Oceanic and Atmospheric Administration (NOAA) is a clear demonstration that many scientists agree that simple model calculations of the type used in the TTAPS paper have identified a problem of potentially great scientific and human interest.

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